CMOS Analog IC Design [2019 -2020]
OTA Design Example[1]

Tutorial 4

1 SCL180 Process Parameters [Estimated]

$$\boxed{\mu_n = 300\,\mathrm{cm^2/Vs};\ \mu_p = 70\,\mathrm{cm^2/Vs}}$$

$$t_{ox} = 4\,\mathrm{nm} \implies C_{ox} = \frac{\epsilon_{ox}\cdot\epsilon_0}{t_{ox}} = \frac{3.97\times 8.85\times 10^{-12}(\mathrm{F\,m^{-1}})}{(40\times 10^{-10})\mathrm{m}}$$

$$\implies \boxed{C_{ox} = 8.78\,\mathrm{fF/\mu m^2}}$$

$$\begin{aligned} K_n = \mu_n C_{ox} &= 300\,\mathrm{cm^2/Vs}\times 8.78\,\mathrm{fF/\mu m^2} \\ \implies K_n &= 263\,\mathrm{\mu A/V^2} \end{aligned}$$

$$\begin{aligned} K_p = \mu_p C_{ox} &= 70\,\mathrm{cm^2/Vs}\times 8.78\,\mathrm{fF/\mu m^2} \\ \implies K_p &= 62\,\mathrm{\mu A/V^2} \end{aligned}$$

$$\text{For } L = 0.18\,\mathrm{\mu m}\ (\text{min L}),\ \boxed{\lambda_p = 0.328\,\mathrm{V^{-1}},\ \lambda_n = 0.48\,\mathrm{V^{-1}}}$$

$$\boxed{|V_{TP}| = 0.4\,\mathrm{V};\ V_{TN} = 0.48\,\mathrm{V}}$$

2 Specifications

Design a 2 stage OTA with the following specifications:

Parameter	Specification
Voltage Gain (A_v)	$\geq 66\,\mathrm{dB}$
Unity Gain Frequency (f_u)	$\geq 100\,\mathrm{MHz}$
V_{DD}	$1.8\,\mathrm{V}$
Slew Rate	$\geq 100\,\mathrm{V/\mu s}$
Output Swing	$\geq 1.3\,\mathrm{V_{pp}}$
I/P Referred White Noise (Thermal only)	$\leq 8\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
Phase Margin	$60°$

3 Chosen Architecture

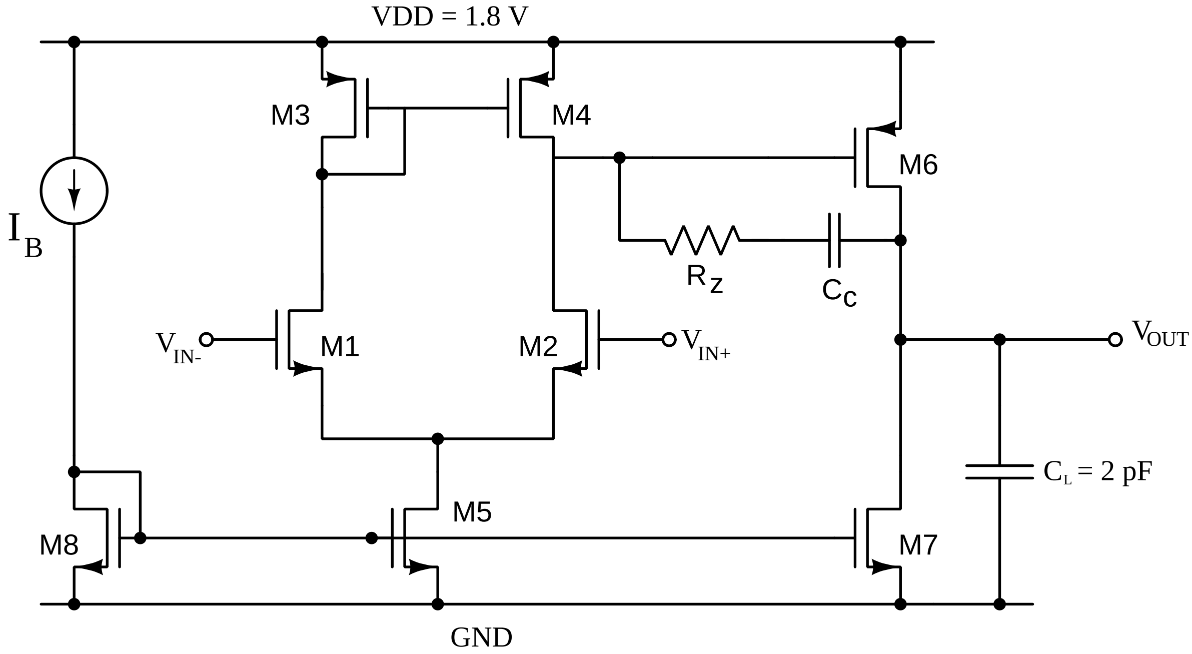

Figure 1: Basic 2-Stage OTA with Frequency Compensation and Zero Nulling

References

[1] G. Palmisano, G. Palumbo, and S. Pennisi, “Design Procedure for two-stage CMOS Transconductance Operational Amplifiers: A Tutorial,” *Analog Integrated Circuits and Signal Processing*, vol. 27, pp. 179–189, May 2001.

FROM L-15, opamp i/p referred noise

$$\overline{V}^2_{neq} = 2\left[\overline{v}^2_{n_1} + \overline{v}^2_{n_3}\left(\frac{g_{m_3}}{g_{m_1}}\right)^2\right] \quad \text{Thermal Noise only}$$

$$= 2\left[4KT\frac{2}{3}\frac{1}{g_{m_1}} + 4KT\frac{2}{3}\frac{1}{g_{m_3}}\left(\frac{g_{m_3}}{g_{m_1}}\right)^2\right]$$

$$= \frac{16KT}{3}\cdot\frac{1}{g_{m_1}}\left[1 + \frac{g_{m_3}}{g_{m_1}}\right]$$

Assuming $g_{m_3} \ll g_{m_1}$

$$\overline{v}^2_{neq} = \frac{16KT}{3}\cdot\frac{1}{g_{m_1}} = \left(8\,nV/\sqrt{Hz}\right)^2$$

$$g_{m_1} = \frac{16KT}{3\cdot\left(8\,nV/\sqrt{Hz}\right)^2}$$

$$= \frac{16\times 1.38\times 10^{-23}\times 300}{3\times 64\times 10^{-18}}\ S$$

$$= 345\ \mu S$$

From L-11 page(3-4.)

$$UGF = f_{GBW} = DC\text{ gain}\times P_D$$

$$= \frac{g_{m_1}}{g_B}\cdot\frac{g_{m_6}}{g_C}\cdot\frac{g_B/C_c}{(g_{m_6}/g_c)} = \frac{g_{m_1}}{C_c}$$

Remember $\omega_u = 2\pi f_u = g_{m_1}/C_c$

$$C_c = \frac{g_{m_1}}{2\pi f_u} = \frac{345\ \mu S}{2\pi \times 100\ MHz}$$

$$= 0.55\ pF$$

Slew Rate (L – 13 page 6)

$$\frac{dV_{out}}{dt} = \frac{I_{ss}}{C_c}$$ (i/p diff pair lim Slew rate)

$$I_{ss} = C_c \cdot \frac{dV_{out}}{dt} = 0.55\,pF \times 100\,V/\mu s$$

$$I_{ss} = 55\ \mu A \quad \Rightarrow I_{ss} \geq 55\ \mu A.$$

Similarly $I_{oss} = \left(1 + \frac{C_L}{C_c}\right) I_{ss}$ (o/p Slew Rate limit)

$$= \left(1 + \frac{2pF}{0.55pF}\right) 55\ \mu A$$

$$= 255\ \mu A$$

$$\Rightarrow I_{oss} \geq 255\ \mu A$$

Figuring out M_1 & M_2 diff pair sizes. —

$$g_{m_1} = \sqrt{2 I_1 K_n \left(\frac{W}{L}\right)_1} = \sqrt{2 \frac{I_{ss}}{2} K_n \left(\frac{W}{L}\right)_1}$$

$$\left(\frac{W}{L}\right)_1 = \frac{g_{m_1}^2}{I_{ss} \cdot K_n} = \frac{(345\ \mu S)^2}{(55\mu A) \times (263\ \mu A/V^2)}$$

$$\left(\frac{W}{L}\right)_1 = \underline{8.23}$$

Assuming two pole (dom & non-dom) response.

$$\text{Phase Margin} = 90 - \tan^{-1}\left(\frac{f_{GBW}}{f_{ND}}\right)$$

(for example if $f_{ND} = f_{GBW}$
$PM = 45°$.)

For $PM = 60°$

$$\Rightarrow \quad f_{ND} = \left[\tan(90-60°)\right]^{-1} f_{GBW}$$

$$= \frac{100\,MHz}{\tan(30)} = 173.2\,MHz$$

$$= \frac{g_{m6}}{C_L} \cdot \frac{1}{2\pi}$$

$$\Rightarrow \quad g_{m6} = 2\pi C_L \times 173.2 \times 10^6$$

$$= 2\pi \times 2 \times 10^{-12} \times 173.2 \times 10^6$$

$$= 2.176\,mS$$

$$\left(\frac{W}{L}\right)_6 = \frac{g_{m6}^2}{2 K_p I_{oss}} = \frac{(2.176 \times 10^{-3})^2}{2 \times 62\,\mu/V^2 \times 255\,\mu A}$$

$$= \frac{(2176)^2 \mu^2 S^2}{2 \times 62\,\mu/V^2 \times 255\,\mu A} = 150$$

From (L-12 p.2)

If we push RH zero to infinity $R_Z = \frac{1}{g_{m6}}$

$$\Rightarrow \quad R_Z = \frac{1}{2.176\,mS} = 460\,\Omega$$

If we line up RHP zero on Non-dom pole

$$R_Z = \frac{1}{g_{m6}}\left(1 + \frac{C_L}{C_c}\right) = 460\left(1 + \frac{2}{0.55}\right)$$

$$= 2.132\ k\Omega$$ → This Choice would improve PM further.

Swing $1.3\ V_{pp} \Rightarrow V_{dsatp} = V_{dsatn} = 250\,mV$ (Output devices)

$$V_{dsat6} = \sqrt{\frac{2 I_{oss}}{K_p\left(\frac{W}{L}\right)_6}} = \sqrt{\frac{2 \times 255\,\mu A}{62\,\mu A/V^2 \times 150}}$$

$$= 234\,mV \qquad \text{OK.}$$

$$V_{dsat7} = \sqrt{\frac{2 I_{oss}}{K_n\left(\frac{W}{L}\right)_7}} \Rightarrow \left(\frac{W}{L}\right)_7 = \frac{2 I_{oss}}{K_n \cdot V_{dsat7}^2}$$

$$\left(\frac{W}{L}\right)_7 = \frac{2 \times 255\,\mu A}{263\,\mu A/V^2 \times 0.0625\,V^2}$$

$$\left(\frac{W}{L}\right)_7 = 31$$

For zero systematic offset.

$$V_{dsat3} = V_{dsat4} = V_{dsat6} = 234\,mV$$

$$\left(\frac{W}{L}\right)_{3,4} = \frac{I_{ss}/2}{I_{oss}} \times \left(\frac{W}{L}\right)_6 = \frac{55/2}{255} \times 150$$

$$= 16.2$$

Gain Spec $A_v = A_{v_1} A_{v_2}$

$$A_{v_1} = \frac{g_{m_1}}{g_{ds_2} + g_{ds_4}} = \frac{\sqrt{2 K_n (W/L)_1 I_{ss}/2}}{(\lambda_n + \lambda_p) \, I_{ss}/2}$$

$$= \sqrt{\frac{2 K_n (W/L)_1}{I_{ss}/2}} \cdot \frac{1}{(\lambda_n + \lambda_p)}$$

$$= \sqrt{\frac{2 \times 263 \times 8.23}{55/2}} \, \frac{1}{(\lambda_n + \lambda_p)}$$

$$= \frac{12.54}{(\lambda_n + \lambda_p)}$$

$$A_{v_2} = \frac{g_{m_6}}{g_{ds_6} + g_{ds_7}} = \frac{\sqrt{2 K_p (W/L)_6 \cdot I_{oss}}}{(\lambda_n + \lambda_p) I_{oss}}$$

$$= \sqrt{\frac{2 K_p (W/L)_6}{I_{oss}}} \cdot \frac{1}{(\lambda_n + \lambda_p)}$$

$$= \sqrt{\frac{2 \times 62 \times 150}{255}} \cdot \frac{1}{(\lambda_n + \lambda_p)} = \frac{8.54}{(\lambda_n + \lambda_p)}$$

66 dB gain $\Rightarrow$ $2000 = A_v$

$$2000 = A_{v_1} \cdot A_{v_2} = \frac{12.54}{(\lambda_p + \lambda_n)} \cdot \frac{8.54}{(\lambda_p + \lambda_n)}$$

assume all λ equal

$$2000 = \frac{107.09}{4\lambda^2} \Rightarrow \lambda = \underline{0.1156}$$

Note $\lambda_1 L_1 = \lambda_2 L_2$ (1, 2 Not for transistors)

For PMOS $\lambda_1 = 0.328\,V^{-1}$ for $L_1 = 0.18\,\mu m$

for desired $\lambda_2 = 0.1156$

pmos $L_2 = \dfrac{0.328 \times 0.18}{0.1156}\,\mu m$

$= 0.510\,\mu m$ Roundup to $0.6\,\mu m$

For NMOS $\lambda_1 = 0.48$ for $L_1 = 0.18\,\mu m$

for desired $\lambda_2 = 0.1156$

nmos $L_2 = \dfrac{0.48 \times 0.18}{0.1156} = 0.747\,\mu m$

Roundup to $0.8\,\mu m$

Reference

Design Procedure for 2-stage OTA. —
G. Palmisano — AICSP - 27 - 2001
Kluwer

Complete schematic