Simple OTA

Key specifications:

- $A_v \geq 20 \text{dB}$
- $G_m \approx 1 \text{mA/V}$
- $A_{cm} \leq -40 \text{dB}$

* For $G_m \approx 1 \text{mA/V}$ spec:

$$G_m = g_m = \sqrt{2 \mu C_k \left( \frac{W}{L} \right)} = 1 \text{mA/V}$$

* For $A_v \geq 20 \text{dB} = 10$ spec:

$$A_v = \frac{g_{m1}}{g_{o1} + g_{o2}} = \frac{1 \text{mA/V}}{\frac{I_b}{2} (\lambda_N + \lambda_P)} \geq 10$$

$$\Rightarrow I_b \leq \frac{2 \text{mA/V}}{10(\lambda_N + \lambda_P)}$$

* For $A_{cm} \leq -40 \text{dB}$ spec

$$A_{cm} = -\frac{1}{2g_{m2} R_{\text{TAIL}}}$$

The following design procedure and results are from Amandeep Singh.
Homework #5
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$L_3$ Since we want high gain from $M_6$, choose $L = 2.4 \mu H$ for $M_5$ & $M_6$.

$L_3$ Length for other transistors $M_3-M_4$ is chosen $L = 1.2 \mu H$.

$L_3$ Required transconductance gain, $g_m = 1 \text{mV/V}.$

$L_3$ For $g_m = g_m = g_m.$

$L_3$ Choosing a value of $g_m/I_0 = 10$ for $M_3-M_4$ to keep transistors in saturation and also have reasonable output swing,

$$\text{(I_0) m_1 = (I_0) m_2 = (I_0) m_3 = (I_0) m_4 = 100 \mu A}.$$  

$$\omega_c = (I_0) m_5 = (I_0) m_6 = 200 \mu A.$$  

$L_3$ For $M_5$ & $M_6$  \( L = 2.4 \mu H \)  \( \omega_c = 10 \) corresponds to $f_{0.6} = 2.064 \mu m / \mu m$.

$$w_{m_5,m_6} = \frac{200 \mu A}{0.6146 \mu m} = 3.35 \mu m \text{ (rounded to quad size)}.$$

$L_3$ For $M_1$ & $M_2$  \( L = 1.2 \mu H \)  \( \omega_c = 10 \) corresponds to $f_{0.5} = 2.223 \mu m / \mu m$.

\[ w = 81.6 \mu m \text{ (rounded to quad size)} \]

$L_3$ For $M_3$ & $M_4$  \( L = 1.2 \mu H \)  \( g_{m_0} = 10 \), $f_{0.5} = 0.522 \mu m / \mu m$.

\[ w = 191 \mu m. \]
Common Mode Gain

Differential Gain
HD3 plots

Transconductance Gain:

\[ V_{i} / I_{o} (\text{PLUS}) \]

\[ M_{0}(1.727\, \text{Hz}, 1.064\, \text{mA}) \]

\[ 165.96\, \text{kHz} \quad -43.00985\, \text{mdeg} \]
Differential Pair Non-Linearity (Razavi 13.1.2)

Theory for Part C

\[
I_{01} - I_{02} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{in} \sqrt{\frac{4I_{ds}}{\mu_n C_{ox} \frac{W}{L}} - V_{in}^2}
\]

\[
= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{in} \sqrt{4(V_{ds} - V_{th})^2 - V_{in}^2}
\]

Assuming devices remain in sat, i.e. \(|V_{in}| \leq V_{ds} - V_{th}

\[
I_{01} - I_{02} = \mu_n C_{ox} \frac{W}{L} V_{in} (V_{ds} - V_{th}) \left[ 1 - \frac{V_{in}^2}{4(V_{ds} - V_{th})^2} \right]
\]

Taylor Expansion \(w\) only 1 term

\[
\sqrt{1-x} \Rightarrow 1 - \frac{x}{2}
\]

\[
I_{01} - I_{02} = \mu_n C_{ox} \frac{W}{L} V_{in} (V_{ds} - V_{th}) \left[ 1 - \frac{V_{in}^2}{8(V_{ds} - V_{th})^2} \right]
\]

\[W'_{ih} = W_n \cos \omega t\]

\[W'_{ih} = \mu_n C_{ox} \frac{W}{L} (V_{ds} - V_{th}) \left[ V_{m} \cos \omega t - \frac{V_{m}^3}{8(V_{ds} - V_{th})^2} \right]
\]

Using Trig Identity \(\cos^3 \omega t = \frac{3}{4} \cos \omega t + \frac{1}{4} \cos 3\omega t\)

\[
I_{01} - I_{02} = V_m \left[ V_m - \frac{3V_m}{32(V_{ds} - V_{th})^2} \right] \cos \omega t - g_m \frac{V_m^3}{32(V_{ds} - V_{th})^2} \cos 3\omega t
\]

\[
A_{Nos} = \frac{V_m^2}{32(V_{ds} - V_{th})^2}
\]

Following Sim results from Harish Krishnamoorthy
(i) The circuit was then simulated using a sinusoidal input signal of 1 MHz, sweeping the amplitude of the differential input signal from 1 mV up to 1.5*VDSAT (184.4mV).

In the picture above, the waveform at the top is the ratio of 3rd harmonic content to the fundamental at 1MHz. It can be observed that it is a parabolic curve in this range. The below waveform is the actual fundamental current at varying input differential voltage. That is linear up to a value and then starts dipping slightly. As input voltage increases, the ratio of 3rd harmonic also increases w.r.t. to the fundamental.

(ii) Then using MS Office Excel, the formula \( HD3=(1/32)\times(Vin-peak/VDSAT)^2 \) was plotted. The graph that came is as below:
Noise Analysis - Thermal Only

\[ i_{o1}^2 = \frac{8}{3} kT g_{m1} \] (1 Diff Pair Transistor)

\[ i_{o2}^2 = \frac{8}{3} kT g_{m2} \] (1 Current Source Load Transistor)

Note, the noise due to any tail current source will be small. For example, if we assume a simple current mirror

\[ i_{o3} = \frac{i_{n3}}{2} - g_{m2} \left[ \frac{i_{n3}}{2} \left( \frac{1}{g_{m2} + g_{01} + g_{02}} \right) \right] \]

\[ = \frac{i_{n3}}{2} \left[ 1 - \frac{g_{m2}}{g_{m2} + g_{01} + g_{02}} \right] = \frac{i_{n3}}{2} \left[ \frac{g_{01} + g_{02}}{g_{m2} + g_{01} + g_{02}} \right] \]

\[ = \frac{i_{n3}}{2} \frac{g_{01} + g_{02}}{g_{m2}} \]

\[ i_{o3}^2 = \frac{8}{3} kT g_{m3} \left( \frac{g_{01} + g_{02}}{2 g_{m2}} \right)^2 \]

Thus, it is okay to neglect tail current source noise.
\[ i_{0}^2 = 2i_{01}^2 + 2i_{02}^2 = \frac{16}{3} kT \left( \frac{g_{m1} + g_{m2}}{g_{m1}} \right) \]

To input refer the noise as \( V_{\text{in}}^2 = \frac{i_{0}^2}{g_{m1}^2} \)

\[ V_{\text{in}}^2 = \frac{16}{3} kT \left( \frac{1}{g_{m1}} \right) \left( 1 + \frac{g_{m2}}{g_{m1}} \right) \]

If we include Flicker (\( 1/f \)) noise

\[ i_{01}^2 = \frac{K_{\text{Fu}} g_{m1}^2}{W_L C_{\text{ox}} f} \]
\[ i_{02}^2 (\frac{1}{f}) = \frac{K_{F} g_{m2}^2}{W_L C_{\text{ox}} f} \]
\[ V_{\text{in}}^2 (\frac{1}{f}) = \frac{K_{\text{FN}}}{W_L C_{\text{ox}} f} + \frac{K_{FP}}{W_L C_{\text{ox}} f} \left( \frac{g_{m2}}{g_{m1}} \right)^2 \]

Total Noise (Thermal + Flicker)

\[ V_{\text{in}}^2 = \frac{16}{3} kT \left( \frac{1}{g_{m1}} \right) \left( 1 + \frac{g_{m2}}{g_{m1}} \right) \frac{K_{\text{FN}}}{(W_L) C_{\text{ox}} f} + \frac{K_{FP}}{(W_L) C_{\text{ox}} f} \left( \frac{g_{m2}}{g_{m1}} \right)^2 \]