Process parameters for the AMI 0.5 micron process.

$V_{TN} := 0.88V$ $\quad V_{TP} := -1.0V$ $\quad n := 1.4$

$K_{PN} := 110\frac{\mu A}{V^2}$ $\quad K_{PP} := 32\frac{\mu A}{V^2}$ $\quad R := \frac{K_{PN}}{K_{PP}} = 3.438$

$C_{ox} := 2.5\cdot 10^{-15}\frac{F}{\mu m^2}$ $\quad C_{ol} := 0.25\cdot 10^{-15}\frac{F}{\mu m}$ $\quad C_{xb} := 0.2\cdot 10^{-15}\frac{F}{\mu m}$

Flicker noise parameters (current noise)

$K_{aP} := 3.8\cdot 10^{-30}A\cdot F$ $\quad K_{aN} := 6.3\cdot 10^{-26}A\cdot F$

Flicker noise current density

$$i_{n2} := \frac{K_a\cdot I_B}{C_{OX}\cdot L^2}\cdot\frac{df}{f}$$

Input refered flicker noise voltage density

$$v_{n2} := \frac{i_{n2}}{g_m^{\ 2}} \rightarrow \frac{I_B\cdot K_a\cdot df}{C_{OX}\cdot L^2\cdot f\cdot g_m^{\ 2}}$$

If the device is strongly inverted then we can write

$$v_{n2} := v_{n2}\ \text{substitute}, g_m = \sqrt{\frac{2\cdot I_B\cdot S\cdot K_P}{n_{sub}}} \rightarrow \frac{K_a\cdot df\cdot n_{sub}}{2\cdot C_{OX}\cdot K_P\cdot L^2\cdot S\cdot f}$$

$$v_{n2} := v_{n2}\ \text{substitute}, S = \frac{W}{L} \rightarrow \frac{K_a\cdot df\cdot n_{sub}}{2\cdot C_{OX}\cdot K_P\cdot L\cdot W\cdot f}$$

$$v_{n2} := v_{n2} \text{ substitute}, \frac{K_a \cdot n_{sub}}{2 \cdot K_P} = K_v \rightarrow \frac{K_v \cdot df}{C_{OX} \cdot L \cdot W \cdot f}$$

So let us compute

$$K_{vP} := \frac{K_{aP} \cdot n}{2 \cdot K_{PP}} = 8.312499999999998 \times 10^{-26} J$$

$$K_{vN} := \frac{K_{aN} \cdot n}{2 \cdot K_{PN}} = 4.009090909090909E\text{-}022 J$$

Other parameters

Thermal voltage: $U_T := 26 \cdot 10^{-3} V$

Electronic charge: $q_e := 1.602 \cdot 10^{-19} C$

IMPORTANT FUNCTIONS

$$THETA\_N(I, S) := \frac{I}{2 \cdot n \cdot S \cdot K_{PN} \cdot U_T^2}$$

$$THETA\_P(I, S) := \frac{I}{2 \cdot n \cdot S \cdot K_{PP} \cdot U_T^2}$$

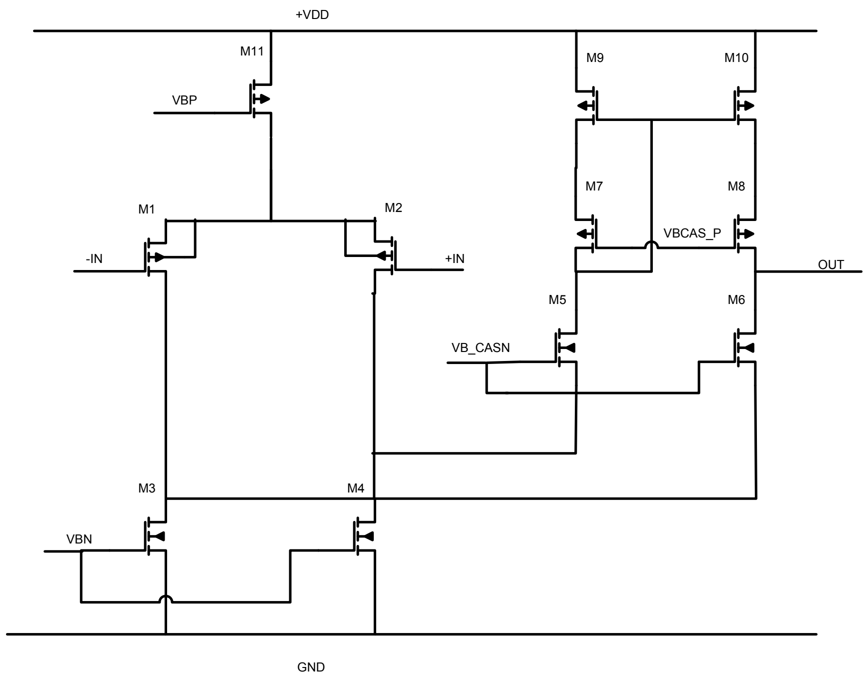
$$VSAT(I, g_m) := 2 \cdot \frac{I}{g_m}$$

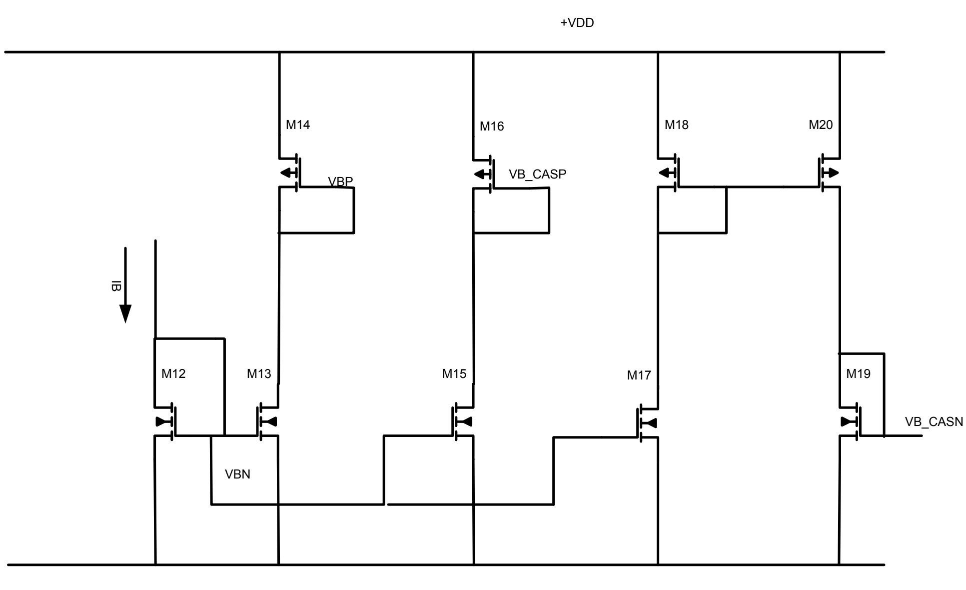
$$RO(I, V_E) := \frac{V_E}{I}$$

$$GMN(I, S) := \left[\begin{array}{l} \left(\theta \leftarrow \frac{I}{2 \cdot n \cdot S \cdot K_{PN} \cdot U_T^2} \right) \\ out \leftarrow \frac{1 - e^{-\sqrt{\theta}}}{\sqrt{\theta}} \cdot \frac{I}{n \cdot U_T} \\ \text{return } out \end{array} \right]$$

$$GMP(I, S) := \left[\begin{array}{l} \left(\theta \leftarrow \frac{I}{2 \cdot n \cdot S \cdot K_{PP} \cdot U_T^2} \right) \\ out \leftarrow \frac{1 - e^{-\sqrt{\theta}}}{\sqrt{\theta}} \cdot \frac{I}{n \cdot U_T} \\ \text{return } out \end{array} \right]$$

FOLDED CASCODE OTA





$C_{Lmin} := 10 \cdot 10^{-12} F$ $C_{Lmax} := 15 \cdot 10^{-12} F$ $V_{pk} := 1.3V$

$T_{settle} := 10\mu s$

Slew rate calculations

$SR = \frac{I_o}{C_L}$ solve, $I_o \rightarrow C_L \cdot SR$

Also $SR := \frac{2 \cdot V_{pk}}{5\mu s} = 5.2 \times 10^5 \frac{m^2 \cdot kg}{A \cdot s^4}$

Use the maximim C_L

$I_o := C_{Lmax} \cdot SR = 7.8 \times 10^{-6} A$

Since I have a 5 uA current source at my disposal lets use

$I_o := 10\mu A$

Compute how long we will slew

$SR := \frac{I_o}{C_{Lmax}} = 6.667 \times 10^5 \frac{m^2 \cdot kg}{A \cdot s^4}$ $T_{slew} := 2 \cdot \frac{V_{pk}}{SR} = 3.9 \times 10^{-6} s$

We want linear settling to ovvur in about 5 μs and to within 0.01%

NumTimeConst := 12 Nine or ten time constants would be enough ...

$t_{linear} = 12 \cdot \tau$ solve, $\tau \rightarrow \frac{t_{linear}}{12}$ $t_{linear} := T_{settle} - T_{slew} = 6.1 \times 10^{-6} s$

$\tau := \frac{t_{linear}}{NumTimeConst} = 5.083 \times 10^{-7} s$ $\omega_u := \frac{1}{\tau} = 1.967 \times 10^6 \frac{1}{s}$

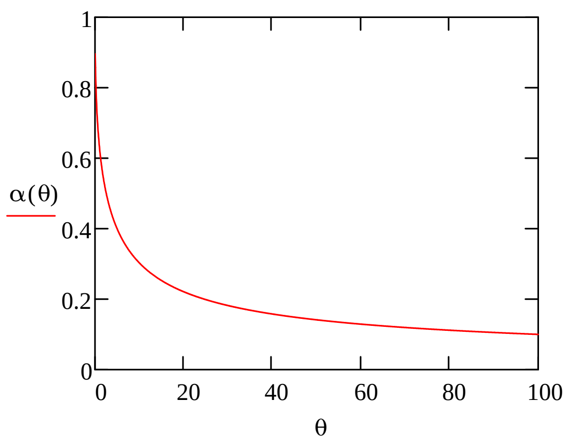
$f_u := \frac{\omega_u}{2 \cdot \pi} = 3.131 \times 10^5 \frac{1}{s}$

$\omega_u = \frac{g_{mi}}{C_L}$ | explicit, solve, $g_{mi} \rightarrow C_L \cdot \omega_u$ $g_{mi} := C_{Lmax} \cdot \omega_u = 2.951 \times 10^{-5} \frac{1}{\Omega}$

$$g_m = \alpha \cdot \frac{I_B}{n \cdot U_T} \;\Big|\; \begin{array}{l}\text{explicit}\\ \text{solve}, \alpha\end{array} \rightarrow \frac{U_T \cdot g_m \cdot n}{I_B}$$

Bias current for input device is 1/2 Io.

$$\alpha := \frac{U_T \cdot g_{mi} \cdot n}{\frac{I_o}{2}} = 0.215 \qquad \alpha(\theta) := \frac{1 - e^{-\sqrt{\theta}}}{\sqrt{\theta}} \qquad \theta := 0.05, 0.1 .. 100$$



$$\theta_{sym} = \frac{I_B}{2 \cdot n \cdot S_1 \cdot K_{PP} \cdot U_T^2} \;\Big|\; \begin{array}{l}\text{explicit}\\ \text{solve}, S_1\end{array} \rightarrow \frac{I_B}{2 \cdot K_{PP} \cdot U_T^2 \cdot n \cdot \theta_{sym}}$$

So choose θ of about 3 $\qquad \theta := 3$

$$S_1 := \frac{\frac{I_o}{2}}{\left(2 \cdot K_{PP} \cdot U_T^2 \cdot n \cdot \theta\right)} = 27.517$$

$$K_{os} := 20\text{mV} \cdot \mu\text{m} \qquad \sigma_{os} = \frac{K_{os}}{\sqrt{A}} \;\Big|\; \begin{array}{l}\text{solve}, A\\ \text{explicit}\end{array} \rightarrow \frac{K_{os}^2}{\sigma_{os}^2}$$

$$\sigma_{os} := 2.5\text{mV} \qquad A_1 := \frac{K_{os}^2}{\sigma_{os}^2} = 6.4 \times 10^{-11}\,\text{m}^2$$

$$A_1 = W_1 \cdot L_1 \;\Big|\; \begin{matrix}\text{explicit}\\ \text{solve}, W_1\end{matrix} \rightarrow \frac{A_1}{L_1}$$

$$S_1 = \frac{W_1}{L_1} \;\Big|\; \begin{matrix}\text{explicit}\\ \text{solve}, W_1\end{matrix} \rightarrow L_1 \cdot S_1$$

$$L_1 \cdot S_1 = \frac{A_1}{L_1} \;\Big|\; \begin{matrix}\text{explicit}\\ \text{solve}, L_1\end{matrix} \rightarrow \begin{pmatrix} -\frac{\sqrt{A_1 \cdot S_1}}{S_1} \\ \frac{\sqrt{A_1 \cdot S_1}}{S_1} \end{pmatrix}$$

$$L_1 := \sqrt{\frac{A_1}{S_1}} = 1.525 \times 10^{-6}\,\text{m}$$

$$W_1 := \frac{A_1}{L_1} = 4.196 \times 10^{-5}\,\text{m}$$

$$g_{m1} := \text{GMP}\left(\frac{I_o}{2}, S_1\right) = 6.528 \times 10^{-5}\,\frac{1}{\Omega}$$

Recall we wanted: $g_{mi} = 2.951 \times 10^{-5}\,\frac{1}{\Omega}$

Having a bit more than what we wanted is a good thing ....

Compute the output resistance.

$$V_{E1} := 15\text{V} \qquad r_{ds1} := \text{RO}\left(\frac{I_o}{2}, V_{E1}\right) = 3 \times 10^{6}\,\Omega \qquad g_{ds1} := \frac{1}{r_{ds1}} = 3.333 \times 10^{-7}\,\frac{1}{\Omega}$$

Check the thermal noise

$$\text{NBW} := \frac{\pi}{2} \cdot f_u = 4.918 \times 10^{5}\,\frac{1}{\text{s}}$$

$$v_t := \sqrt{2} \cdot \sqrt{4 \cdot U_T \cdot q_e \cdot \frac{2}{3} \cdot \frac{1}{g_{m1}} \cdot \text{NBW}} = 1.294 \times 10^{-5}\,\text{V}$$

Check the 1/f noise

$$v_f := \sqrt{2} \cdot \sqrt{\frac{K_{vP}}{C_{ox} \cdot W_1 \cdot L_1} \cdot \ln\left(\frac{f_u}{1\text{Hz}}\right)} = 3.626 \times 10^{-6}\,\text{V}$$

Choose transconductance of load devices 2 times smaller than input transconductance. The load device is biased at a * Io.

$$a := 1.5$$

$g_{m3} := \frac{1}{2} \cdot g_{m1} = 3.264 \times 10^{-5} \frac{1}{\Omega}$ $\quad S_3 := \frac{g_{m3}^{2} \cdot n}{2 \cdot a \cdot I_o \cdot K_{PN}} = 0.452$

Choose $W_3 := 6\mu m$ $\quad L_3 := \frac{W_3}{S_3} = 1.328 \times 10^{-5} m$

Compute output resistance

$V_{E3} := 120V$ $\quad r_{ds3} := RO\left(\frac{3 \cdot I_o}{2}, V_{E3}\right) = 8 \times 10^{6} \Omega$ $\quad g_{ds3} := \frac{1}{r_{ds3}} = 1.25 \times 10^{-7} \frac{1}{\Omega}$

Check the saturation voltage on the input and load devices

$V_{ds1\_sat} := VSAT\left(\frac{I_o}{2}, g_{m1}\right) = 0.153 V$

$V_{ds3\_sat} := VSAT\left(a \cdot I_o, g_{m3}\right) = 0.919 V$

Looks reasonable.

SIze the transistor that provides the tail current (M11)

Choose a saturation voltage of 250 mV.

$$V_{ds11\_sat} = \sqrt{\frac{2 \cdot I_o \cdot n}{S_{11} \cdot K_{PP}}} \; \left| \begin{array}{l} \text{explicit} \\ \text{solve}, S_{11} \end{array} \right. \rightarrow \frac{2 \cdot I_o \cdot n}{K_{PP} \cdot V_{ds11\_sat}^{2}}$$

$V_{ds11\_sat} := 0.75V$

$$S_{11} := \frac{2 \cdot I_o \cdot n}{K_{PP} \cdot V_{ds11\_sat}^{2}} = 1.556$$

Choose $L_{11} := 8\mu m$ $\quad W_{11} := S_{11} \cdot L_{11} = 1.244 \times 10^{-5} m$

Compute output resistance.

$V_{E11} := 55V$ $\quad r_{ds11} := RO\left(I_o, V_{E11}\right) = 5.5 \times 10^{6} \Omega$

Compute CMRRR.

$CMRR := 1 + 2 \cdot g_{m1} \cdot r_{ds11} = 719.029$ $CMRR\_DB := 20 \cdot \log(CMRR) = 57.135$

A little shy but not bad .. we will leave it ride for the moment.

Might make sense to see what simulator says before we worry about this.

Compute transconductance.

$$gm_{11} := GMP\left(I_o, S_{11}\right) = 2.667 \times 10^{-5} \frac{1}{\Omega}$$

Make M9 saturation voltage match that of M3.

$$\sqrt{\frac{2 \cdot I_o \cdot n}{S_9 \cdot K_{PP}}} = \sqrt{\frac{2 \cdot \left(\frac{3}{2} \cdot I_o\right) \cdot n}{S_3 \cdot K_{PN}}} \;\Bigg|\; \begin{matrix} \text{explicit} \\ \text{solve}, S_9 \end{matrix} \rightarrow \frac{2 \cdot K_{PN} \cdot S_3}{3 \cdot K_{PP}}$$

$$S_9 := \frac{2 \cdot K_{PN} \cdot S_3}{3 \cdot K_{PP}} = 1.036$$

Choose $L_9 := 10\mu m$ $W_9 := S_9 \cdot L_9 = 1.036 \times 10^{-5} m$

Find output resistance.

$V_{E9} := 65V$ $r_{ds9} := RO\left(I_o, V_{E9}\right) = 6.5 \times 10^{6} \Omega$ $g_{ds9} := \frac{1}{r_{ds9}} = 1.538 \times 10^{-7} \frac{1}{\Omega}$

Choose a saturation voltage of about 200 mV for M7 so as to meet our swing requirement.

$$V_{ds7\_sat} = \sqrt{\frac{2 \cdot I_o \cdot n}{S_7 \cdot K_{PP}}} \;\Bigg|\; \begin{matrix} \text{explicit} \\ \text{solve}, S_7 \end{matrix} \rightarrow \frac{2 \cdot I_o \cdot n}{K_{PP} \cdot V_{ds7\_sat}^{2}}$$

$$V_{ds7\_sat} := 200mV$$

$$S_7 := \frac{2 \cdot I_o \cdot n}{K_{PP} \cdot V_{ds7\_sat}^{2}} = 21.875$$

Choose $L_7 := 2\mu m$ $W_7 := S_7 \cdot L_7 = 4.375 \times 10^{-5} m$

Compute the output resistance and transconductance.

$V_{E7} := 20V$ $\quad r_{ds7} := RO(I_o, V_{E7}) = 2\times10^{6}\Omega$ $\quad g_{ds7} := \frac{1}{r_{ds7}} = 5\times10^{-7}\frac{1}{\Omega}$

$g_{m7} := GMP(I_o, S_7) = 9.359\times10^{-5}\frac{1}{\Omega}$

Make M5 and M7 have the same saturation voltage

$$S_5 := \frac{2\cdot I_o\cdot n}{K_{PN}\cdot V_{ds7\_sat}^{2}} = 6.364$$

Choose $\quad L_5 := 4\mu m \quad W_5 := S_5\cdot L_5 = 2.545\times10^{-5}m$

Compute transconductance and output resistance.

$g_{m5} := GMN(I_o, S_5) = 9.359\times10^{-5}\frac{1}{\Omega}$

$V_{E5} := 65V$ $\quad r_{ds5} := RO(I_o, V_{E5}) = 6.5\times10^{6}\Omega$ $\quad g_{ds5} := \frac{1}{r_{ds5}} = 1.538\times10^{-7}\frac{1}{\Omega}$

Let us turn our attention to the biasing circuits.

We need the following to be true.

$$\sqrt{\frac{2\cdot I_o\cdot n}{S_{16}\cdot K_{PP}}} = \sqrt{\frac{2\cdot I_o\cdot n}{S_7\cdot K_{PP}}} + \sqrt{\frac{2\cdot I_o\cdot n}{S_9\cdot K_{PP}}} \;\Bigg|\; \begin{matrix}\text{explicit}\\ \text{solve}, S_{16}\end{matrix} \rightarrow \frac{I_o\cdot n}{K_{PP}\cdot\left(\sqrt{\frac{I_o\cdot n}{K_{PP}\cdot S_7}} + \sqrt{\frac{I_o\cdot n}{K_{PP}\cdot S_9}}\right)^{2}}$$

$$S_{16} := \frac{1}{\left(\sqrt{\frac{1}{S_7}} + \sqrt{\frac{1}{S_9}}\right)^{2}} = 0.699$$

Choose $\quad L_{16} := 10\mu m \quad W_{16} := S_{16}\cdot L_{16} = 6.986\times10^{-6}m$

Actually made if 7 over 12 for safety.

For completeness compute transconductance and output resistance.

$$g_{m16} := GMP\left(I_o, S_{16}\right) = 1.787 \times 10^{-5}\,\frac{1}{\Omega}$$

We also need

$$\sqrt{\frac{2 \cdot I_o \cdot n}{S_{19} \cdot K_{PN}}} = \sqrt{\frac{2 \cdot \left(\frac{3 \cdot I_o}{2}\right) \cdot n}{S_3 \cdot K_{PN}}} + \sqrt{\frac{2 \cdot I_o \cdot n}{S_5 \cdot K_{PN}}} \;\Bigg|\; \begin{array}{l}\text{explicit} \\ \text{solve}, S_{19}\end{array} \rightarrow \frac{I_o \cdot n}{K_{PN} \cdot \left(\sqrt{\frac{I_o \cdot n}{K_{PN} \cdot S_5}} + \frac{\sqrt{2} \cdot \sqrt{3} \cdot \sqrt{\frac{I_o \cdot n}{K_{PN} \cdot S_3}}}{2}\right)^2}$$

$$S_{19} := \frac{I_o \cdot n}{K_{PN} \cdot \left(\sqrt{\frac{I_o \cdot n}{K_{PN} \cdot S_5}} + \frac{\sqrt{2} \cdot \sqrt{3} \cdot \sqrt{\frac{I_o \cdot n}{K_{PN} \cdot S_3}}}{2}\right)^2} \;\Bigg|\; \begin{array}{l}\text{explicit} \\ \text{simplify}\end{array} \rightarrow \frac{4 \cdot I_o \cdot n}{K_{PN} \cdot \left(2 \cdot \sqrt{\frac{I_o \cdot n}{K_{PN} \cdot S_5}} + \sqrt{\frac{6 \cdot I_o \cdot n}{K_{PN} \cdot S_3}}\right)^2}$$

$$S_{19} := \frac{4 \cdot I_o \cdot n}{K_{PN} \cdot \left(2 \cdot \sqrt{\frac{I_o \cdot n}{K_{PN} \cdot S_5}} + \sqrt{\frac{6 \cdot I_o \cdot n}{K_{PN} \cdot S_3}}\right)^2} = 0.203$$

Choose $L_{19} := 20\mu m$ $W_{19} := S_{19} \cdot L_{19} = 4.064 \times 10^{-6}\,m$

Actually made it 4.1 over 22 for safety.

$$g_{m19} := GMN\left(I_o, S_{19}\right) = 1.787 \times 10^{-5}\,\frac{1}{\Omega}$$

$$V_{ds19\_sat} := VSAT\left(I_o, g_{m19}\right) = 1.119\,V$$

Compute output resistance for OTA.

$$R_{on} := (g_{m5} \cdot r_{ds5}) \cdot \frac{1}{g_{ds1} + g_{ds3}} = 1.327 \times 10^{9}\,\Omega \qquad G_{on} := \frac{1}{R_{on}} = 7.534 \times 10^{-10}\,\frac{1}{\Omega}$$

$$R_{op} := (g_{m7} \cdot r_{ds7}) \cdot r_{ds9} = 1.217 \times 10^{9}\,\Omega \qquad G_{op} := \frac{1}{R_{op}} = 8.219 \times 10^{-10}\,\frac{1}{\Omega}$$

$$R_{out} := \frac{1}{G_{on} + G_{op}} = 6.348 \times 10^{8}\,\Omega$$

Compute the low-frequency imbalance factor.

$$k := \frac{(r_{ds7} \cdot g_{m7} \cdot r_{ds9}) \cdot (g_{ds1} + g_{ds3})}{g_{m5} \cdot r_{ds5}} = 0.917$$

$$A_o := \left(\frac{2 + k}{2 + 2 \cdot k}\right) \cdot g_{m1} \cdot R_{out} = 3.153 \times 10^{4} \qquad A_{dB} := 20 \cdot \log(A_o) = 89.974$$

We easily met the open-loop gain spec.

Compute the dominant pole frequency.

$$\omega_d := \frac{1}{R_{out} \cdot C_{Lmax}} = 105.023\,\frac{1}{s} \qquad f_d := \frac{\omega_d}{2 \cdot \pi} = 16.715\,\frac{1}{s}$$

$$f_u := \frac{g_{m1}}{2 \cdot \pi \cdot C_{Lmax}} = 6.926 \times 10^{5}\,\frac{1}{s}$$

Acutally about ten times faster than we need. It was because of the severe slew rate requirement we had.

$$C_{db1} := C_{xb} \cdot W_1 = 8.393 \times 10^{-15}\,F$$

$$C_{db3} := C_{xb} \cdot W_3 = 1.2 \times 10^{-15} F$$

$$C_{gs5} := \frac{2}{3} \cdot C_{ox} \cdot W_5 \cdot L_5 = 169.697 \times 10^{-15} F$$

$$C_{db5} := C_{xb} \cdot W_5 = 5.091 \times 10^{-15} F$$

$$C_{gd5} := C_{ol} \cdot W_5 = 6.364 \times 10^{-15} F$$

$$C_x := C_{db1} + C_{db3} + C_{gs5} + C_{db5} + 2 \cdot C_{gd5} = 1.971 \times 10^{-13} F$$

Just guessing that this might be the most important parasitic pole.

$$\omega_p := \frac{g_{m5}}{C_x} = 4.748 \times 10^{8} \frac{1}{s} \qquad f_p := \frac{\omega_p}{2 \cdot \pi} = 7.557 \times 10^{7} \frac{1}{s}$$

The phase margin should be near 90 degrees.