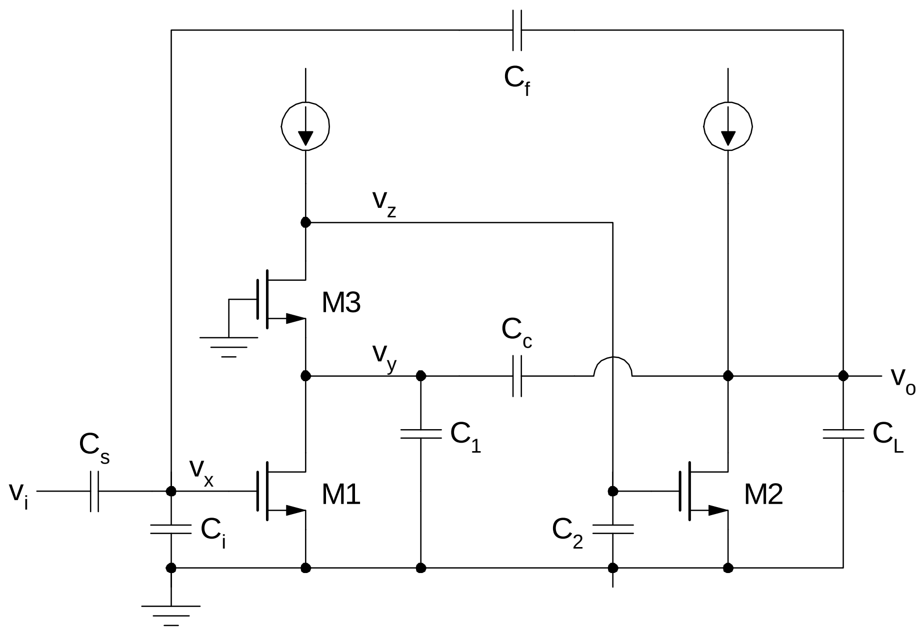
Reference:D:\Users\Bernhard\Lib\MathCAD\Default\defaults.mcd

2-Stage OTA with Cascode Compensation

References:

K. Nakamura et al, "An 85 mW, 10 b, 40 Msample/s CMOS Parallel-Pipelined ADC," IEEE Journal of Solid-State Circuits, Vol. 30, No. 3, pp. 173-183, March 1995.

D.B. Ribner and M.A Copeland, "Design Techniques for Cascoded CMOS Op Amps with Improved PSRR and Common-Mode Input Range," IEEE Journal of Solid-State Circuits, Vol. Sc-19, No. 6, pp. 919-925, December 1984.



Openloop Analysis

Given

$$v_y \cdot s \cdot (C_1 + C_c) + v_y \cdot g_{m3} - v_o \cdot s \cdot C_c + v_x \cdot g_{m1} = 0$$

$$v_z \cdot s \cdot C_2 - v_y \cdot g_{m3} = 0$$

$$v_o \cdot s \cdot (C_L + C_c) - v_y \cdot s \cdot C_c + v_z \cdot g_{m2} = 0$$

$$\mathrm{Find}(v_o, v_y, v_z) \rightarrow \begin{bmatrix} -v_x \cdot g_{m1} \cdot \dfrac{(s^2 \cdot C_c \cdot C_2 - g_{m2} \cdot g_{m3})}{\left[(s^2 \cdot C_2 \cdot C_L \cdot C_1 + s^2 \cdot C_2 \cdot C_L \cdot C_c + s \cdot C_2 \cdot C_L \cdot g_{m3} + s^2 \cdot C_2 \cdot C_c \cdot C_1 + s \cdot C_2 \cdot C_c \cdot g_{m3} + g_{m3} \cdot g_{m2} \cdot C_c) \cdot s\right]} \\ -s \cdot C_2 \cdot v_x \cdot g_{m1} \cdot \dfrac{(C_L + C_c)}{(s^2 \cdot C_2 \cdot C_L \cdot C_1 + s^2 \cdot C_2 \cdot C_L \cdot C_c + s \cdot C_2 \cdot C_L \cdot g_{m3} + s^2 \cdot C_2 \cdot C_c \cdot C_1 + s \cdot C_2 \cdot C_c \cdot g_{m3} + g_{m3} \cdot g_{m2} \cdot C_c)} \\ -v_x \cdot g_{m1} \cdot \dfrac{(C_L + C_c)}{(s^2 \cdot C_2 \cdot C_L \cdot C_1 + s^2 \cdot C_2 \cdot C_L \cdot C_c + s \cdot C_2 \cdot C_L \cdot g_{m3} + s^2 \cdot C_2 \cdot C_c \cdot C_1 + s \cdot C_2 \cdot C_c \cdot g_{m3} + g_{m3} \cdot g_{m2} \cdot C_c)} \cdot g_{m3} \end{bmatrix}$$

$$a(s) = \frac{v_o}{v_x} = g_{m1}\cdot\frac{\left(-C_2\cdot C_c\cdot s^2 + g_{m3}\cdot g_{m2}\right)}{\left[\left(s^2\cdot C_2\cdot C_L\cdot C_1 + s^2\cdot C_2\cdot C_L\cdot C_c + s\cdot C_2\cdot C_L\cdot g_{m3} + s^2\cdot C_2\cdot C_c\cdot C_1 + s\cdot C_2\cdot C_c\cdot g_{m3} + g_{m3}\cdot g_{m2}\cdot C_c\right)\cdot s\right]}$$

$$a(s) = \frac{g_{m1}\cdot g_{m2}\cdot g_{m3}}{s}\cdot\frac{1 - s^2\cdot\frac{C_c\cdot C_2}{g_{m2}\cdot g_{m3}}}{s^2\cdot\left(C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1\right) + s\cdot\left(C_2\cdot C_L\cdot g_{m3} + C_2\cdot C_c\cdot g_{m3}\right) + g_{m3}\cdot g_{m2}\cdot C_c}$$

$$a(s) = \frac{g_{m1}}{2\cdot C_c}\cdot\frac{1}{s^2\cdot\frac{C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1}{C_c\cdot g_{m2}\cdot g_{m3}} + s\cdot\frac{C_2}{C_c}\cdot\frac{C_L + C_c}{g_{m2}} + 1}$$

poles:

Given

$$s^2\cdot\left(\frac{C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1}{C_c\cdot g_{m2}\cdot g_{m3}}\right) + s\cdot\left(\frac{C_2}{C_c}\cdot\frac{C_L + C_c}{g_{m2}}\right) + 1 = 0$$

$$\text{Find}(s) \rightarrow \left[\frac{1}{\left[2\cdot\left(C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1\right)\right]}\cdot\left[-C_2\cdot g_{m3}\cdot C_c - C_2\cdot g_{m3}\cdot C_L + \left(C_2^{\,2}\cdot g_{m3}^{\,2}\cdot C_c^{\,2} + 2\cdot C_2^{\,2}\cdot g_{m3}^{\,2}\cdot C_c\cdot C_L + C_2^{\,2}\cdot g_{m3}^{\,2}\cdot C\right.\right.\right.$$

$p_1 = 0$ $\quad p_2 = -\omega_n\cdot\left(1 + \sqrt{D}\right)$ $\quad p_2 = -\omega_n\cdot\left(1 - \sqrt{D}\right)$

$$\omega_n = \frac{C_2\cdot g_{m3}\cdot\left(C_L + C_c\right)}{2\cdot\left(C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1\right)} = \frac{g_{m3}\cdot\left(C_L + C_c\right)}{2\cdot\left[C_L\cdot\left(C_1 + C_c\right) + C_c\cdot C_1\right]}$$

approximation $\quad C_1 < \blacksquare < C_c , C_L$

$$\omega_n = \frac{g_{m3}\cdot\left(C_L + C_c\right)}{2\cdot\left(C_L\cdot C_c + C_c\cdot C_1\right)} = \frac{g_{m3}\cdot\left(C_L + C_c\right)}{2\cdot C_c\cdot C_L} = \frac{g_{m3}}{2\cdot C_c}\cdot\left(1 + \frac{C_c}{C_L}\right)$$

$$D = \frac{C_2^{\,2}\cdot C_L^{\,2}\cdot g_{m3}^{\,2} + 2\cdot C_2^{\,2}\cdot C_L\cdot g_{m3}^{\,2}\cdot C_c + C_2^{\,2}\cdot C_c^{\,2}\cdot g_{m3}^{\,2} - 4\cdot C_c\cdot g_{m2}\cdot g_{m3}\cdot C_2\cdot C_L\cdot C_1 - 4\cdot C_c^{\,2}\cdot g_{m2}\cdot g_{m3}\cdot C_2\cdot C_L - 4\cdot C_c^{\,2}\cdot g_{m2}\cdot g_{m3}\cdot C_2\cdot C_1}{2\cdot\left(C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1\right)}$$

$$a(s) = \frac{g_{m1}}{s\cdot C_c}\cdot\frac{1 - \frac{s^2}{z^2}}{\left(1 - \frac{s}{p_1}\right)\cdot\left(1 - \frac{s}{p_2}\right)}$$

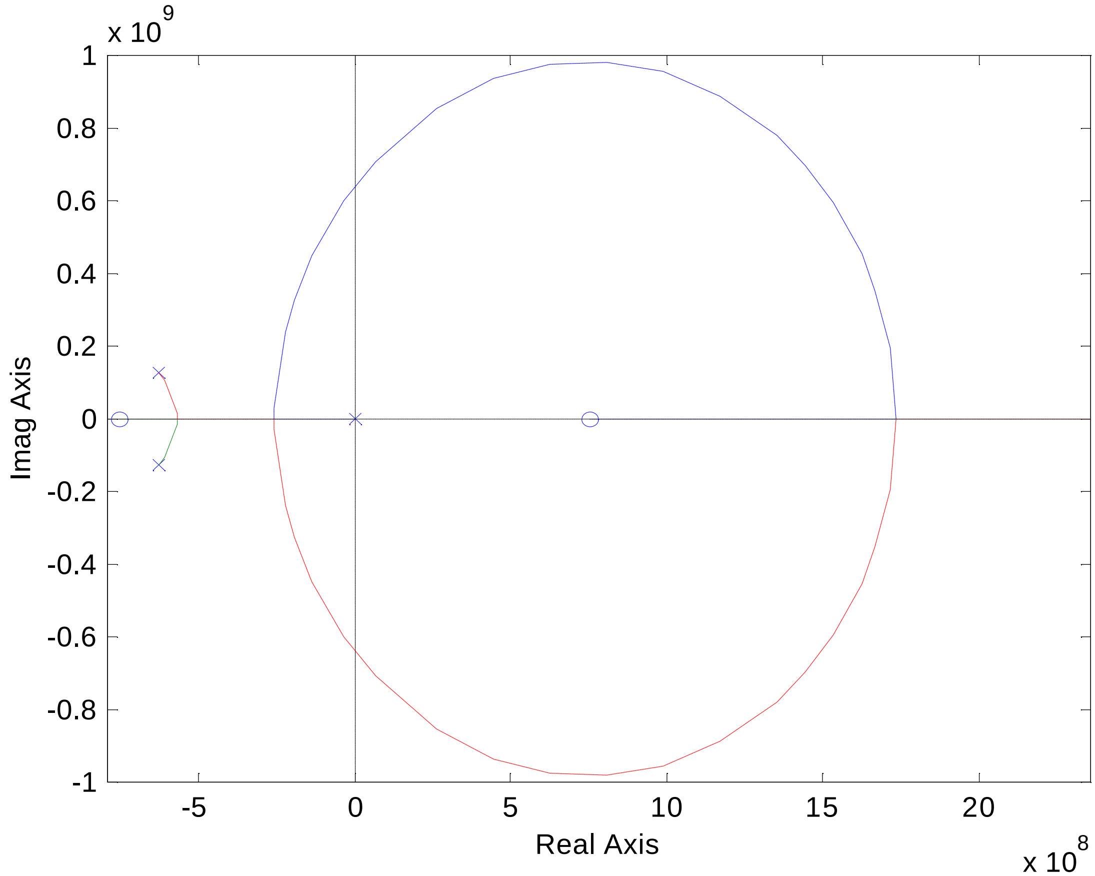
- real zeros at +/- z (phase cancels)
- pole at zero
- poles p1, p2 (usually close or complex conjugates)

$$\omega_n = \frac{g_{m3}}{2\cdot C_c}\cdot\left(1 + \frac{C_c}{C_L}\right)$$

$z_1 = \sqrt{\frac{g_{m2}\cdot g_{m3}}{C_2\cdot C_c}}$ $\quad z_2 = -\sqrt{\frac{g_{m2}\cdot g_{m3}}{C_2\cdot C_c}}$

phase lag from RHP zero cancelled by lead from LHP zero

Root Locus


x 10^9
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Imag Axis
-5
0
5
10
15
20
Real Axis
x 10^8

Closed-Loop Analysis ($k=g_{m1}$)

Given

Note: strictly this is a multi-loop feedback circuit and the Bode criterion (for establishing stability) does not apply.

$$v_x \cdot C_{Tx} - v_o \cdot C_f = 0$$

$$v_y \cdot s \cdot (C_1 + C_c) + v_y \cdot g_{m3} - v_o \cdot s \cdot C_c - i_t = 0$$

$$v_z \cdot s \cdot C_2 - v_y \cdot g_{m3} = 0$$

$$v_o \cdot s \cdot C_{To} - v_y \cdot s \cdot C_c - v_x \cdot s \cdot C_f + g_{m2} \cdot v_z = 0$$

$$\mathrm{Find}(v_x, v_y, v_z, v_o) \rightarrow \begin{bmatrix} -i_t \cdot \dfrac{}{\left[\left(-s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_1 - s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_c - s \cdot C_2 \right.\right.} \\ -s \cdot C_2 \cdot i_t \cdot \dfrac{}{\left(-s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_1 - s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_c - \right.} \\ -i_t \cdot \dfrac{}{\left(-s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_1 - s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_c - s \cdot C_2 \right.} \\ -i_t \cdot C_{Tx} \cdot \dfrac{}{\left[\left(-s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_1 - s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_c - \right.\right.} \end{bmatrix}$$

$$T = \frac{i_r}{i_t} = \frac{g_{m1} \cdot v_x}{i_t}$$

$$T = g_{m1} \cdot \left[\frac{\left(-C_2 \cdot C_c \cdot s^2 + g_{m2} \cdot g_{m3}\right)}{\left[\left(s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_1 + s^2 \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_c + s \cdot C_2 \cdot C_{To} \cdot C_{Tx} \cdot g_{m3} - s^2 \cdot C_2 \cdot C_f^2 \cdot C_1 - s^2 \cdot C_2 \cdot C_f^2 \cdot C_c - s \cdot C_2 \cdot C_f^2 \cdot g_{m3} - s^2 \cdot C_c^2 \cdot C_{Tx} \cdot C \right.\right.} \right.$$

$$a = C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_1 + C_2 \cdot C_{To} \cdot C_{Tx} \cdot C_c - C_2 \cdot C_f^2 \cdot C_1 - C_2 \cdot C_f^2 \cdot C_c - C_c^2 \cdot C_{Tx} \cdot C_2$$

$$a = C_2 \cdot C_{To} \cdot C_{Tx} \cdot (C_1 + C_c) - C_2 \cdot C_f^2 \cdot (C_1 + C_c) - C_c^2 \cdot C_{Tx} \cdot C_2$$

assume C1 << Cc

$$a = C_2 \cdot C_c \cdot \left(C_{To} \cdot C_{Tx} - C_f^2 - C_c \cdot C_{Tx}\right)$$

$$b = C_2 \cdot C_{To} \cdot C_{Tx} \cdot g_{m3} - C_2 \cdot C_f^2 \cdot g_{m3} = g_{m3} \cdot C_2 \cdot \left(C_{To} \cdot C_{Tx} - C_f^2\right)$$

$$c = g_{m2} \cdot g_{m3} \cdot C_{Tx} \cdot C_c$$

$$T = \frac{F \cdot \omega_u}{s} \cdot \frac{\left(1 - \dfrac{s}{z_1}\right) \cdot \left(1 - \dfrac{s}{z_2}\right)}{\left(1 - \dfrac{s}{p_2}\right) \cdot \left(1 - \dfrac{s}{p_3}\right)}$$

$$p_1 = 0 \qquad p_2 = -\omega_n \cdot \left(1 + \sqrt{D}\right) \qquad p_3 = -\omega_n \cdot \left(1 - \sqrt{D}\right)$$

$$z_1 = \sqrt{\frac{g_{m2} \cdot g_{m3}}{C_2 \cdot C_c}} \qquad z_2 = -\sqrt{\frac{g_{m2} \cdot g_{m3}}{C_2 \cdot C_c}}$$

$$\omega_n = \frac{b}{2 \cdot a} = \frac{1}{2} \cdot \frac{g_{m3} \cdot C_2 \cdot \left(C_{To} \cdot C_{Tx} - C_f^2\right)}{C_2 \cdot C_c \cdot \left(C_{To} \cdot C_{Tx} - C_f^2 - C_c \cdot C_{Tx}\right)} = \frac{g_{m3}}{2 \cdot C_c} \cdot \frac{1}{1 - \dfrac{C_c \cdot C_{Tx}}{C_{To} \cdot C_{Tx} - C_f^2}} = \frac{g_{m3}}{2 \cdot C_c} \cdot \frac{1}{1 - \dfrac{C_c}{C_{To} - F \cdot C_f}}$$

$$\omega_n = \frac{g_{m3}}{2 \cdot C_c} \cdot \frac{1}{1 - \dfrac{C_c}{C_{To} - F \cdot C_f}}$$

$$D = 1 - \frac{4a \cdot c}{b^2} = 1 - \frac{4 \cdot C_2 \cdot C_c \cdot \left(C_{To} \cdot C_{Tx} - C_f^2 - C_c \cdot C_{Tx}\right) \cdot g_{m2} \cdot g_{m3} \cdot C_{Tx} \cdot C_c}{\left[g_{m3} \cdot C_2 \cdot \left(C_{To} \cdot C_{Tx} - C_f^2\right)\right]^2} = 1 - 4 \cdot \frac{g_{m2}}{g_{m3}} \cdot \frac{C_c}{C_2} \cdot \frac{C_c \cdot C_{Tx}}{C_{To} \cdot C_{Tx} - C_f^2} \cdot \left(1 - \frac{C_c \cdot C_{Tx}}{C_{To} \cdot C_{Tx} - C_f^2}\right)$$

$$D = 1 - 4 \cdot \frac{g_{m2}}{g_{m3}} \cdot \frac{C_c}{C_2} \cdot \frac{C_c \cdot C_{Tx}}{C_{To} \cdot C_{Tx} - C_f^2} \cdot \left(1 - \frac{C_c}{C_{To} - F \cdot C_f}\right)$$

Example:

closed-loop gain: $c := 2$

devices:

$g_{m1} := 1\text{mS}$ $\quad g_{m2} := 3\text{mS}$ $\quad g_{m3} := 1.2\text{mS}$

$\omega_{T1} := 0.5\cdot\text{GHz}\cdot 2\cdot\pi$ $\quad \omega_{T2} := 2\cdot\omega_{T1}$ $\quad \omega_{T3} := 2\cdot\omega_{T1}$

$C_i := \dfrac{g_{m1}}{\omega_{T1}}$ $\quad C_2 := \dfrac{g_{m2}}{\omega_{T2}}$ $\quad C_1 := \dfrac{g_{m3}}{\omega_{T3}}$

$C_i = 318.31\,\text{fF}$ $\quad C_2 = 477.465\,\text{fF}$ $\quad C_1 = 190.986\,\text{fF}$

feedback network:

$C_s := C_i$ $\quad C_s = 318.31\,\text{fF}$

$C_f := \dfrac{C_2}{c}$ $\quad C_f = 238.732\,\text{fF}$

load and compensation:

$C_L := 1\text{pF}$

$C_c := 1.2\cdot\dfrac{g_{m1}}{g_{m2}}\cdot C_L$ $\quad C_c = 400\,\text{fF}$

shorthands:

$C_{Tx} := C_s + C_f + C_i$ $\quad C_{Tx} = 875.352\,\text{fF}$

$C_{To} := C_L + C_c + C_f$ $\quad C_{To} = 1.639\times 10^3\,\text{fF}$

$F := \dfrac{C_f}{C_{Tx}}$ $\quad F = 0.273$

$\omega_u := \dfrac{g_{m1}}{C_c}$ $\quad \dfrac{\omega_u}{2\cdot\pi} = 397.887\,\text{MHz}$

Solution:

$$T = \frac{F\cdot\omega_u}{s}\cdot\frac{\left(1-\frac{s}{z_1}\right)\cdot\left(1-\frac{s}{z_2}\right)}{\left(1-\frac{s}{p_2}\right)\cdot\left(1-\frac{s}{p_3}\right)} = \frac{F\cdot\omega_u}{s}\cdot\frac{\left(1-\frac{s}{z_1}\right)\cdot\left(1-\frac{s}{z_2}\right)}{1+\frac{s}{Q\cdot\omega_r}+\frac{s^2}{\omega_r^{\,2}}}$$

$\dfrac{\omega_u}{2\pi} = 397.887\,\text{MHz}$

$\dfrac{F\cdot\omega_u}{2\pi} = 108.515\,\text{MHz}$

$z_1 := \sqrt{\dfrac{g_{m2}\cdot g_{m3}}{C_c\cdot C_2}}$ $\quad \dfrac{z_1}{2\pi} = 690.988\,\text{MHz}$

$z_2 := -\sqrt{\dfrac{g_{m2}\cdot g_{m3}}{C_c\cdot C_2}}$ $\quad \dfrac{z_2}{2\pi} = -690.988\,\text{MHz}$

$\omega_n := \dfrac{g_{m3}}{2\cdot C_c}\cdot\dfrac{1}{1-\dfrac{C_c}{C_{To}-F\cdot C_f}}$ $\quad \dfrac{\omega_n}{2\pi} = 320.098\,\text{MHz}$

$D := \left[1-4\cdot\dfrac{g_{m2}}{g_{m3}}\cdot\dfrac{C_c}{C_2}\cdot\dfrac{C_c}{C_{To}-F\cdot C_f}\cdot\left(1-\dfrac{C_c}{C_{To}-F\cdot C_f}\right)\right]$ $\quad D = -0.588$

$p_2 := -\omega_n \cdot \left(1 + \sqrt{D}\right)$ $\qquad \frac{p_2}{2\pi} = -320.098 - 245.497i\,\mathrm{MHz}$

$p_3 := -\omega_n \cdot \left(1 - \sqrt{D}\right)$ $\qquad \frac{p_3}{2\pi} = -320.098 + 245.497i\,\mathrm{MHz}$

$p(s) := \arg\left[\left(1 - \frac{s}{p_2}\right)\cdot\left(1 - \frac{s}{p_3}\right)\right]$ $\qquad p\left(j \cdot F \cdot \omega_u\right) = 24.712\,\mathrm{deg}$

$\Phi_m(s) := \frac{\pi}{2} - p(s)$ Phase margin $\qquad \Phi_m\left(j \cdot F \cdot \omega_u\right) = 65.288\,\mathrm{deg}$

Design Considerations

Closed-loop bandwidth: $\omega_{3dB} := F \cdot \omega_u$

Nondominiant pole frequencies (real part only): $\omega_n := \frac{g_{m3}}{2 \cdot C_c} \cdot \frac{1}{1 - \frac{C_c}{C_{To} - F \cdot C_f}}$

For 60 deg phase margin K=2 (approximate):
Factor 2 since there are two nondominant poles)

$\omega_n = 2 \cdot K \cdot \omega_{3dB}$

$$2 \cdot KF \cdot \frac{g_{m1}}{C_c} = \frac{g_{m3}}{2 \cdot C_c} \cdot \frac{1}{1 - \frac{C_c}{C_{To} - F \cdot C_f}}$$

$$K := \frac{1}{4 \cdot F} \cdot \frac{g_{m3}}{g_{m1}} \cdot \frac{F \cdot C_f - C_{To}}{F \cdot C_f - C_{To} + C_c} \qquad K := \frac{1}{4 \cdot F} \cdot \frac{g_{m3}}{g_{m1}} \cdot \frac{1}{1 - \frac{C_c}{C_{To} - F \cdot C_f}}$$

$K = 1.475$

Increasing K increases the phase margin.

$$_L{}^2 - 4\cdot g_{m3}\cdot g_{m2}\cdot C_c\cdot C_2\cdot C_L\cdot C_1 - 4\cdot g_{m3}\cdot g_{m2}\cdot C_c{}^2\cdot C_2\cdot C_L - 4\cdot g_{m3}\cdot g_{m2}\cdot C_c{}^2\cdot C_2\cdot C_1\Big)^{\left(\frac{1}{2}\right)}\Bigg] \quad \frac{1}{\left[2\cdot\left(C_2\cdot C_L\cdot C_1 + C_2\cdot C_L\cdot C_c + C_2\cdot C_c\cdot C_1\right)\right]}\cdot\Bigg[-C_2\cdot g_m$$

$$\frac{\left(s^2\cdot C_c\cdot C_2 - g_{m3}\cdot g_{m2}\right)}{\cdot C_{To}\cdot C_{Tx}\cdot g_{m3} + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_1 + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_c + s\cdot C_2\cdot C_f^{\,2}\cdot g_{m3} + s^2\cdot C_c^{\,2}\cdot C_{Tx}\cdot C_2 - g_{m2}\cdot g_{m3}\cdot C_{Tx}\cdot C_c\big)\cdot s\big]}\cdot C_f$$

$$\frac{\left(C_{To}\cdot C_{Tx} - C_f^{\,2}\right)}{s\cdot C_2\cdot C_{To}\cdot C_{Tx}\cdot g_{m3} + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_1 + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_c + s\cdot C_2\cdot C_f^{\,2}\cdot g_{m3} + s^2\cdot C_c^{\,2}\cdot C_{Tx}\cdot C_2 - g_{m2}\cdot g_{m3}\cdot C_{Tx}\cdot C_c\big)}$$

$$\frac{\left(C_{To}\cdot C_{Tx} - C_f^{\,2}\right)}{\cdot C_{To}\cdot C_{Tx}\cdot g_{m3} + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_1 + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_c + s\cdot C_2\cdot C_f^{\,2}\cdot g_{m3} + s^2\cdot C_c^{\,2}\cdot C_{Tx}\cdot C_2 - g_{m2}\cdot g_{m3}\cdot C_{Tx}\cdot C_c\big)}\cdot g_{m3}$$

$$\frac{\left(s^2\cdot C_c\cdot C_2 - g_{m3}\cdot g_{m2}\right)}{s\cdot C_2\cdot C_{To}\cdot C_{Tx}\cdot g_{m3} + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_1 + s^2\cdot C_2\cdot C_f^{\,2}\cdot C_c + s\cdot C_2\cdot C_f^{\,2}\cdot g_{m3} + s^2\cdot C_c^{\,2}\cdot C_{Tx}\cdot C_2 - g_{m2}\cdot g_{m3}\cdot C_{Tx}\cdot C_c\big)\cdot s\big]}\Bigg]$$

$$\frac{}{{}_2 + g_{m2}\cdot g_{m3}\cdot C_{Tx}\cdot C_c\big)\cdot s\big]}\cdot C_f\Bigg]$$

$$\cdot C_c - C_2 \cdot g_{m3} \cdot C_L - \left(C_2^{\,2} \cdot g_{m3}^{\,2} \cdot C_c^{\,2} + 2 \cdot C_2^{\,2} \cdot g_{m3}^{\,2} \cdot C_c \cdot C_L + C_2^{\,2} \cdot g_{m3}^{\,2} \cdot C_L^{\,2} - 4 \cdot g_{m3} \cdot g_{m2} \cdot C_c \cdot C_2 \cdot C_L \cdot C_1 - 4 \cdot g_{m3} \cdot g_{m2} \cdot C_c^{\,2} \cdot C_2 \cdot C_L - 4 \cdot g_{m3} \cdot g_{m}\right.$$

$$\cdot C_c^{2} \cdot C_2 \cdot C_1 \Big)^{\left(\frac{1}{2}\right)} \Big] \Big]$$