Sallen-Key Low Pass Filter Design Routine

v_i

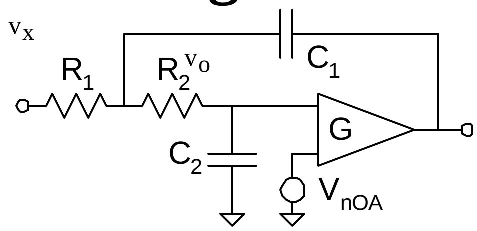


Fig. 1: Single-ended Sallen-Key filter

Note: This routine is a reduction of a more complex version. This reduction is still taking place, so please excuse the current mess.

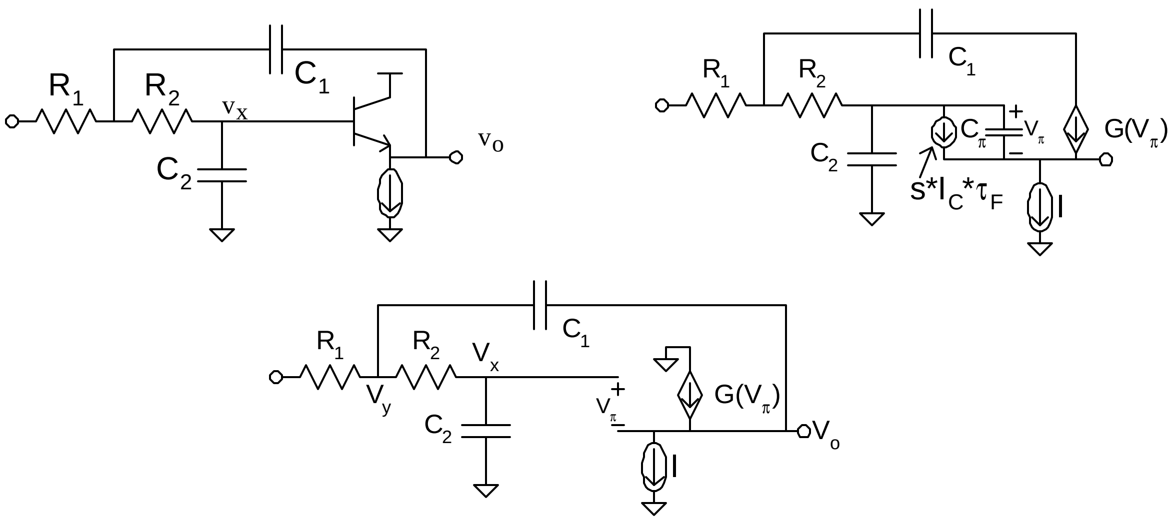


Fig. 2: Single-Ended Sallen-Key Filter w/ Emitter Follower

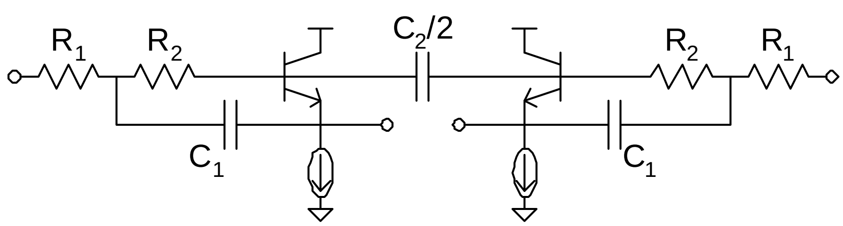


Fig. 3: Differential Voltage-Driven Sallen-Key Filter

▶ useful functions and identities

▶ Units

▶ Constants

▶ Units/Constants/Model File

$$V_o = \frac{V_i}{\left[1 + (R_2 + R_1)\cdot C_2\cdot s + R_1\cdot R_2\cdot C_1\cdot C_2\cdot s^2\right]} = \frac{1}{\left(\frac{s}{\omega_0}\right)^2 + \frac{s}{\omega_0}\cdot\frac{1}{Q} + 1}$$

Ideal Transfer Function

$$\omega_0 = \frac{1}{\sqrt{R_1\cdot R_2\cdot C_1\cdot C_2}} \qquad \omega_1 = \frac{1}{R_1\cdot C_1} \qquad A = g_m\cdot R_1$$

$Q = \frac{1}{\ldots}$

$$Q = \frac{\quad}{C_2 \cdot \omega_0 \cdot (R_1 + R_2)}$$

$$V_T := \frac{k \cdot Temp}{q} \qquad V_T = 25.899\,mV \qquad g_m = \frac{I_C}{V_T} \qquad Den = 1 + \frac{1}{\omega_0 \cdot Q} \cdot s + \left(\frac{s}{\omega_0}\right)^2$$

$$A_1(s) = \frac{\left[\left[1 + \left(\frac{s \cdot \omega_1}{\omega_0^{\,2}}\right)\right] \cdot \frac{s}{A \cdot \omega_1} + 1\right]}{\left[\left(1 + \frac{s}{Q \cdot \omega_0}\right) \cdot \frac{s}{A \cdot \omega_1} + Den(s)\right]}$$

$$A_{max} = \frac{1}{\left(\frac{1}{Q} \cdot \frac{\omega_0}{\omega_1} + g_m \cdot R_1\right)}$$ Maximum Attenuation with a fast transistor

$$f_{notch} = \omega_0 \cdot \sqrt{A}$$ Frequency of the Notch

$$A_{notch} := \frac{1}{A}$$ Attenuation of the Notch

Equivalent Noise Bandwidth

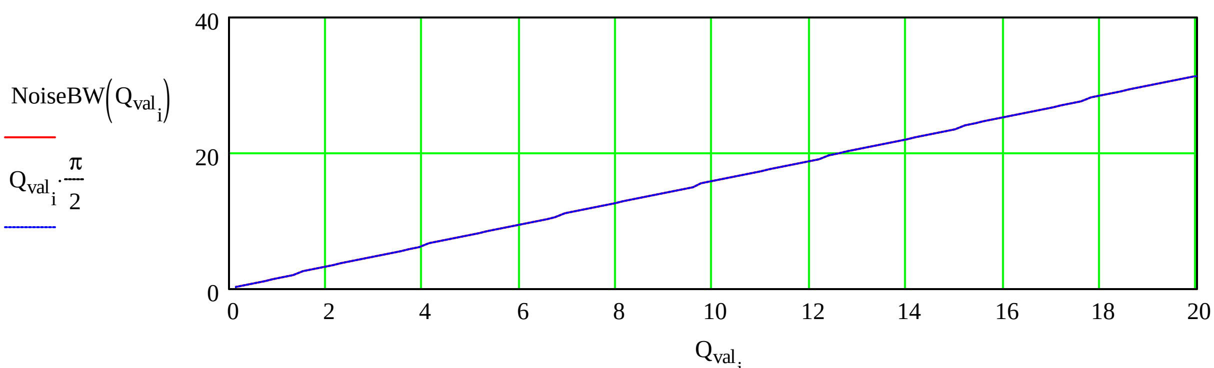
$$H_{LPF}(s, G, \omega_0, Q) := \frac{G}{\left(\frac{s}{\omega_0}\right)^2 + \frac{s}{\omega_0} \cdot \frac{1}{Q} + 1}$$ Frequency Response - General LPF Representation (no zeros):

$$NoiseBW(Q) := \int_0^{10000} \left(\left|H_{LPF}\left(\sqrt{-1} \cdot 2 \cdot \pi \cdot f, 1, 2 \cdot \pi, Q\right)\right|\right)^2 df$$

$num := 100$ **Number of Points for Plotting**

$i := 1 .. num$ Index Vector for Plotting

$$Q_{val_i} := \frac{i-1}{num-1} \cdot (20 - 0.1) + 0.1$$



Derivation

First Use KCL to solve for the transfer functions for the system

KCL @ Node Vx $$\frac{V_i - V_x}{R_1} = \frac{\left[V_x - \left(\frac{V_o}{G} + V_n\right)\right]}{R_2} + (V_x - V_o) \cdot C_1 \cdot s$$

KCL @ Node Vo/G $$\frac{V_x - \left(\frac{V_o}{G} + V_n\right)}{R_2} = \left(\frac{V_o}{G} + V_n\right) \cdot C_2 \cdot s$$

$$V_o = \frac{-\left[R_1 \cdot C_1 \cdot R_2 \cdot C_2 \cdot s^2 + \left[\frac{C_2}{C_1} \cdot \left(\frac{R_2}{R_1} + 1\right) + 1\right] \cdot R_1 \cdot C_1 \cdot s + 1\right]}{R_1 \cdot C_1 \cdot R_2 \cdot C_2 \cdot s^2 + \left[\frac{C_2}{C_1} \cdot \left(\frac{R_2}{R_1} + 1\right) + 1 - G\right] \cdot R_1 \cdot C_1 \cdot s + 1} \cdot G \cdot V_n \ldots$$

$$+ \frac{G \cdot V_i}{R_1 \cdot C_1 \cdot R_2 \cdot C_2 \cdot s^2 + \left[\frac{C_2}{C_1} \cdot \left(\frac{R_2}{R_1} + 1\right) + 1 - G\right] \cdot R_1 \cdot C_1 \cdot s + 1}$$

$$\omega_0 = \frac{1}{\sqrt{R_1 \cdot C_1 \cdot R_2 \cdot C_2}}$$

$$Q = \frac{\omega_0}{\frac{1}{R_1 \cdot C_1} + \frac{1}{R_2 \cdot C_1} + \frac{1 - G}{R_2 \cdot C_2}} \qquad Q = \frac{1}{\left[\frac{C_2}{C_1} \cdot \left(\frac{R_2}{R_1} + 1\right) + 1 - G\right] \cdot R_1 \cdot C_1 \cdot \omega_0}$$

$$V_{neq}^2 = 4 \cdot k \cdot Temp \cdot (R_1 + R_2) + V_n^2$$

$$V_{oeq}^2 = V_{neq}^2 \cdot \left(\left|H_{LPF}(s, G, \omega_0, Q)\right|\right)^2$$

What is important is the integrated noise.

$$V_{oeq}^2 = V_{neq}^2 \cdot f_0 \cdot NoiseBW \cdot G^2$$

$$V_{neq}^2 = \frac{V_{oeq}^2}{f_0 \cdot NoiseBW \cdot G^2}$$

Inputs

$f_0 := \frac{1.227MHz}{2}$	$f_0 = 613.5\,kHz$	**Center Frequency**
$Q := 0.7071$		**Desired Q**
$SNR := 80dB$		**Minimum Signal to Noise Ratio**
$V_{DD} := 2.7V$		**Supply Voltage**
$Temp := 300K$		**Temperature Range**
$G := 1$		**Gain**
$P_{jammer} := -30dBm$		**Power of the Jammer**
$P_{signal} := -80dBm$		**Power of the Desired Signal**
$f_{jammer} := 900kHz$		**Frequency of Jammer**
$f_{jammer2} := 1700kHz$		**Frequency of Second Jammer** (for Two-Tone Analysis)

Optional Inputs

$V_{DSsat} := 0.3V$	V_{DSsat} of Op-Amp Input
$R_{maxdes} := 400k\Omega$	Maximum Desired Resistor

Calculations

$\omega_0 := 2 \cdot \pi \cdot f_0$

Effective Noise Bandwidth

$NoiseBW(Q) = 1.111$

$V_{inswing} := V_{DD} - 2 \cdot V_{DSsat}$ $\qquad V_{inswing} = 2.1\,V$

$V_{outswing} := V_{inswing} \cdot \left|H_{LPF}(j \cdot 2 \cdot \pi \cdot f_{jammer}, G, \omega_0, Q)\right|$ $\qquad V_{outswing} = 0.885\,V$

$V_{rms} := \frac{V_{inswing}}{2 \cdot \sqrt{2}}$ $\qquad V_{rms} = 0.742\,V$

$$V_{neq} := \frac{V_{rms}}{10^{\frac{SNR}{20}}} \cdot \frac{1}{\sqrt{f_0 \cdot NoiseBW(Q)}} \qquad V_{neq} = 89.943 \frac{nV}{\sqrt{Hz}}$$

$$V_{oeq} := V_{neq}^{2} \cdot f_0 \cdot NoiseBW(Q) \cdot G^{2} \qquad \sqrt{V_{oeq}} = 74.246\,\mu V$$

$$V_n := \frac{V_{neq}}{\sqrt{4}} \qquad V_n = 44.971 \frac{nV}{\sqrt{Hz}}$$

Solving Assumption Number 1: $R_1 = R_2$

$$G_{thresh} := \frac{1}{8 \cdot Q^{2}} + 1 \qquad G_{thresh} = 1.25$$

G should be less than or equal to one

$$valid_r := G \le \frac{1}{8 \cdot Q^{2}} + 1 \qquad valid_r = 1$$

$$R := \frac{V_{neq}^{2} - V_n^{2}}{2 \cdot 4 \cdot k \cdot Temp} \qquad R = 182.794\,k\Omega$$

$$R := if(R > 100k\Omega, 100k\Omega, R) \qquad R = 100\,k\Omega$$

$$R_{1r} := R$$

$$R_{2r} := R$$

$$C_{2r} := \frac{1 + \sqrt{\left[1 - 8 \cdot Q^{2} \cdot (G - 1)\right]}}{4 \cdot Q \cdot \omega_0 \cdot R} \qquad C_{2r} = 1.834\,pF$$

Problem with the $R_1 = R_2$ architecture. C1 blows up for large Q's.

$$C_{1r} := \frac{1}{\omega_0^{2} \cdot R^{2} \cdot C_{2r}} \qquad C_{1r} = 3.669\,pF$$

$$\omega_{1r} := \frac{1}{R_{1r} \cdot C_{1r}} \qquad \frac{\omega_{1r}}{2 \cdot \pi} = 433.814\,kHz$$

$$\omega_{0r} := \frac{1}{\sqrt{R_{1r} \cdot R_{2r} \cdot C_{1r} \cdot C_{2r}}} \qquad \frac{\omega_{0r}}{2 \cdot \pi} = 613.5\,kHz$$

$$Q_r := \frac{\omega_0}{\frac{1}{R_{1r} \cdot C_{1r}} + \frac{1}{R_{2r} \cdot C_{1r}} + \frac{1 - G}{R_{2r} \cdot C_{2r}}} \qquad Q_r = 0.707$$

The following current should be sized much higher to reduce the distortion of the amplifier.

$$\Delta Voutswing\_\Delta t := V_{outswing} \cdot 2 \cdot \pi \cdot f_{jammer}$$

Crude Estimate of Load Capacitance

$$C_{Leff} := C_{1r} \qquad C_{Leff} = 3.669\,pF$$

Estimated Load Capacitance

$$I_{slewr} := C_{Leff} \cdot \Delta Voutswing\_\Delta t \qquad I_{slewr} = 0.018\,mA$$

Required Current to Slew Output

$$I_{noiser} := \frac{\left[4 \cdot k \cdot Temp \cdot \left(\frac{V_T}{2}\right)\right]}{V_n^{2}} \qquad I_{noiser} = 0.106\,\mu A$$

$$I_r := if(I_{slewr} > I_{noiser}, I_{slewr}, I_{noiser}) \qquad I_r = 0.018\,mA$$

$$I_r := if(I_r < I_{min}, I_{min}, I_r)$$

$$g_{mr} := \frac{I_r}{V_T} \qquad g_{mr} = 0.709 \frac{mA}{V}$$

$$A_r := g_{mr} \cdot R \qquad A_r = 70.887$$

$A_r := g_{mr} \cdot R_{1r}$ $A_r = 70.887$

$$A_{maxr} := \frac{1}{\left(\frac{1}{Q} \cdot \frac{\omega_0}{\omega_{1r}} + g_{mr} \cdot R_{1r}\right)}$$ $20 \cdot \log(A_{maxr}) = -37.253\,dB$ Maximum Attenuation with a fa

$$f_{notchr} := \frac{\omega_0}{2 \cdot \pi} \cdot \sqrt{A_r}$$ $f_{notchr} = 5.165\,MHz$ Frequency of the Notch

$$A_{notchr} := \frac{1}{A_r}$$ $20 \cdot \log(A_{notchr}) = -37.011\,dB$

$$area_{Rr} := W_{min} \cdot \frac{(R_{1r} + R_{2r}) \cdot W_{min}}{R_{sq}}$$ $\sqrt{area_{Rr}} = 10\,\mu m$

$cost_{Rr} := cost\_mm2 \cdot area_{Rr}$ $cost_{Rr} = 1.2 \times 10^{-3}\,cent$

$$area_{Cr} := \frac{1}{C\_area} \cdot (C_{1r} + C_{2r})$$ $\sqrt{area_{Cr}} = 88.666\,\mu m$

$cost_{Cr} := cost\_mm2 \cdot area_{Cr}$ $cost_{Cr} = 0.094\,cent$

$area_r := area_{Cr} + area_{Rr}$ $\sqrt{area_r} = 89.228\,\mu m$

$cost_{powerr} := cost_{power} \cdot I_r \cdot V_{DD}$ $cost_{powerr} = 0.14\,cent$

$cost_r := cost_{Cr} + cost_{Rr} + cost_{powerr}$ $cost_r = 0.236\,cent$

Solving Assumption Number 2: $C_1 = C_2$

$$G_{thresh} := 1 + \frac{1}{Q} - \frac{1}{2 \cdot Q^2}$$ $G_{thresh} = 1.25$ G should be greater than 2

Problem with C1=C2 architecture: Cannot be used with an emitter follower unless Q<1/2.

$$valid_c := G \geq 1 + \frac{1}{Q} - \frac{1}{2 \cdot Q^2}$$ $valid_c = 0$

All G's can be used with $Q < \frac{5}{8}$

$$\left[\frac{V_{neq} - V_n}{4 \cdot k \cdot T} \cdot Q + (1 - G) \cdot Q \cdot R_1\right]^2 + R_1 \cdot \left(R_1 - \frac{V_{neq}^2 - V_n^2}{4 \cdot k \cdot Temp}\right) = 0$$

$$R_{1c} := \left[\frac{\frac{1}{2} - Q^2 \cdot (1 - G)}{(1 - G)^2 \cdot Q^2 + 1}\right] \cdot \frac{V_{neq}^2 - V_n^2}{4 \cdot k \cdot Temp} \cdot \left[1 - \sqrt{1 - \frac{1}{\left[\frac{1}{2 \cdot Q} - Q \cdot (1 - G)\right]^2}}\right]$$

$R_{1c} = 182.794 - 182.79i\,k\Omega$

$$R_{2c} := \left(\frac{V_{neq}^2 - V_n^2}{4 \cdot k \cdot Temp} - R_{1c}\right)$$ $R_{2c} = 182.794 + 182.79i\,k\Omega$

$$C := \frac{1}{\left[R_{1c} + R_{2c} + (1 - G) \cdot R_{1c}\right] \cdot Q \cdot \omega_0}$$ $C = 1.004\,pF$

$C_{1c} := C$

$C_{2c} := C$

$$\omega_{0c} := \frac{1}{\sqrt{R_{1c} \cdot R_{2c} \cdot C_{1c} \cdot C_{2c}}}$$ $\frac{\omega_{0c}}{2 \cdot \pi} = 613.5\,kHz$

$$Q_c := \frac{\omega_0}{\frac{1}{R_{1c} \cdot C_{1c}} + \frac{1}{R_{2c} \cdot C_{1c}} + \frac{1 - G}{R_{2c} \cdot C_{2c}}}$$ $Q_c = 0.707$

$C_{Leff} := C_{1c}$ $C_{Leff} = 1.004\,pF$

$I_{slewc} := C_{Leff} \cdot \Delta Voutswing\_\Delta t$ $I_{slewc} = 5.022\,\mu A$ Required Current to Slew Output

$$I_{noisec} := \frac{\left[4 \cdot k \cdot Temp \cdot \left(\frac{V_T}{2}\right)\right]}{{V_n}^2}$$ $I_{noisec} = 0.106\,\mu A$

$I_c := if(I_{slewc} > I_{noisec}, I_{slewc}, I_{noisec})$ $I_c = 5.022\,\mu A$

$I_c := if(I_c < I_{min}, I_{min}, I_c)$

$$\omega_{1c} := \frac{1}{R_{1c} \cdot C_{1c}}$$ $\frac{\omega_{1c}}{2 \cdot \pi} = 433.814 + 433.806i\,kHz$

$$g_{mc} := \frac{I_c}{V_T}$$ $g_{mc} = 0.386\,\frac{mA}{V}$

$A_c := g_{mc} \cdot R_{1c}$ $A_c = 70.58 - 70.578i$

$$A_{maxc} := \frac{1}{\left(\frac{1}{Q} \cdot \frac{\omega_0}{\omega_{1c}} + g_{mc} \cdot R_{1c}\right)}$$ $20 \cdot \log(|A_{maxc}|) = -40.106\,dB$ Maximum Attenua with a fast transist

$$f_{notchc} := \frac{\omega_0}{2 \cdot \pi} \cdot \sqrt{A_c}$$ $f_{notchc} = 5.663 - 2.346i\,MHz$ Frequency of the

$$A_{notchc} := \frac{1}{A_c}$$ $20 \cdot \log(A_{notchc}) = -39.984 + 6.822i\,dB$ Depth of Notch

$$area_{Rc} := W_{min} \cdot \frac{(R_{1c} + R_{2c}) \cdot W_{min}}{R_{sq}}$$ $\sqrt{area_{Rc}} = 13.52\,\mu m$

$cost_{Rc} := cost\_mm2 \cdot area_{Rc}$ $cost_{Rc} = 2.194 \times 10^{-3}\,cent$

$$area_{Cc} := \frac{1}{C\_area} \cdot (C_{1c} + C_{2c})$$ $\sqrt{area_{Cc}} = 53.547\,\mu m$

$cost_{Cc} := cost\_mm2 \cdot area_{Cc}$ $cost_{Cc} = 0.034\,cent$

$area_c := area_{Cc} + area_{Rc}$ $\sqrt{area_c} = 55.227\,\mu m$

$cost_{powerc} := cost_{power} \cdot I_c \cdot V_{DD}$ $cost_{powerc} = 0.076\,cent$

$cost_c := cost_{Cc} + cost_{Rc} + cost_{powerc}$ $cost_c = 0.113\,cent$

Solving Assumption Number 3: $R_1C_1=R_2C_2=\tau$.

$$G_{thresh} := 2 - \frac{1}{Q}$$ $G_{thresh} = 0.586$

$valid_t := G > G_{thresh}$ $valid_t = 1$

$$R_{2t} := \frac{{V_{neq}}^2 - {V_n}^2}{4 \cdot k \cdot Temp \cdot \left(\frac{1}{Q} + G - 1\right)}$$ $R_{2t} = 258.507\,k\Omega$

$$R_{1t} := \left(\frac{1}{Q} + G - 2\right) \cdot R_{2t}$$ $R_{1t} = 107.081\,k\Omega$

$$C_{1t} := \frac{1}{R_{1t} \cdot \omega_0}$$ $C_{1t} = 2.423\,pF$

$$C_{2t} := \frac{1}{R_{2t} \cdot \omega_0}$$ $C_{2t} = 1.004\,pF$

$$\omega_{0t} := \frac{1}{\sqrt{R_{1t} \cdot R_{2t} \cdot C_{1t} \cdot C_{2t}}}$$ $\frac{\omega_{0t}}{} = 613.5\,kHz$

$\sqrt{R_{1t} \cdot R_{2t} \cdot C_{1t} \cdot C_{2t}}$ $\qquad$ $2 \cdot \pi$

$$Q_t := \frac{\omega_0}{\frac{1}{R_{1t} \cdot C_{1t}} + \frac{1}{R_{2t} \cdot C_{1t}} + \frac{1-G}{R_{2t} \cdot C_{2t}}} \qquad Q_t = 0.707$$

Solving Assumption #4: $C_1 = C_{max}$ or C_{min}.

First solve for maximum Capacitance by setting the cost of the internal capacitor to that of an external capacitor. This upper limit is set when extra pins are available to put a capacitor off-chip.

$$C_{max} := \frac{C\_area}{cost\_mm2} \cdot cost_{Cext} \qquad C_{max} = 183.96\,pF$$

$$Area_{Cmax} := \frac{C_{max}}{C\_area} \qquad \sqrt{Area_{Cmax}} = 512.64\,\mu m$$

If the pins are not available to put the capacitor off-chip, the maximum capacitor size must be re-evaluated using marketing estimates for the amount the chip can sell for, and yields given the larger chip size, and package limits on the die size.

$C_{max} := 100pF$ $\qquad$ **Maximum Desired On-Chip Capacitance**

$$Area_{Cmax} := \frac{C_{max}}{C\_area} \qquad \sqrt{Area_{Cmax}} = 512.64\,\mu m$$

Given the center frequency, maximum capacitor size, and desired SNDR the needed capacitance is given by the following equation to prevent a complex resistor sizing.

$$C_{maxm} := \frac{Q}{\omega_0} \cdot \frac{4 \cdot k \cdot Temp \cdot 4}{V_{neq}^{\;2} - V_n^{\;2}} \qquad C_{maxm} = 2.007\,pF$$

$$Area_{Cmaxm} := \frac{C_{maxm}}{C\_area} \qquad \sqrt{Area_{Cmaxm}} = 53.546\,\mu m$$

Now Solve for Variables

$$C_{1m} := C_{maxm} \cdot 1.05 \qquad C_{1m} = 2.107\,pF$$

$$valid_m := Q < \omega_0 \cdot C_{1m} \cdot \left(\frac{V_{neq}^{\;2} - V_n^{\;2}}{4 \cdot k \cdot Temp \cdot 4} \right) \qquad valid_m = 1$$

$$R_{2m} := \frac{V_{neq}^{\;2} - V_n^{\;2}}{4 \cdot k \cdot Temp \cdot 2} \cdot \left[1 + \sqrt{1 - \frac{(4 \cdot k \cdot Temp) \cdot 4}{\left(V_{neq}^{\;2} - V_n^{\;2}\right)} \cdot \frac{Q}{\omega_0 \cdot C_{1m}}} \right] \qquad R_{2m} = 222.683\,k\Omega$$

$$R_{1m} := \frac{V_{neq}^{\;2} - V_n^{\;2}}{4 \cdot k \cdot Temp} - R_{2m} \qquad R_{1m} = 142.905\,k\Omega$$

$$C_{2m} := \frac{1}{\omega_0^{\;2} \cdot R_{1m} \cdot R_{2m} \cdot C_{1m}} \qquad C_{2m} = 1.004\,pF$$

$$\omega_{0m} := \frac{1}{\sqrt{R_{1m} \cdot R_{2m} \cdot C_{1m} \cdot C_{2m}}} \qquad \frac{\omega_{0m}}{2 \cdot \pi} = 613.5\,kHz$$

$$Q_m := \frac{\omega_0}{\frac{1}{R_{1m} \cdot C_{1m}} + \frac{1}{R_{2m} \cdot C_{1m}} + \frac{1-G}{R_{2m} \cdot C_{2m}}} \qquad Q_m = 0.707$$

$$Q_{maxm} := \omega_0 \cdot C_{1m} \cdot \left(\frac{V_{neq}^{\;2} - V_n^{\;2}}{4 \cdot k \cdot Temp \cdot 4} \right) \qquad Q_{maxm} = 0.742$$

$C_{Leff} := C_{1m}$ $\qquad$ $C_{Leff} = 2.107\,pF$ $\qquad$ Estimated Load Capacitance

$I_{slewm} := C_{Leff} \cdot \Delta Voutswing\_\Delta t$ $\qquad$ $I_{slewm} = 10.546\,\mu A$ $\qquad$ Required Current to Slew Output

$\left[4 \cdot k \cdot Temp \cdot \left(\frac{V_T}{2} \right) \right]$

$I_{noisem} := \frac{[\ldots]}{V_n^{2}}$ $\quad I_{noisem} = 0.106\,\mu A$

$I_m := \mathrm{if}\left(I_{slewm} > I_{noisem}, I_{slewm}, I_{noisem}\right)$

$I_m := \mathrm{if}\left(I_m < I_{min}, I_{min}, I_m\right)$ $\quad I_m = 10.546\,\mu A$

$\omega_{1m} := \frac{1}{R_{1m} \cdot C_{1m}}$ $\quad \frac{\omega_{1m}}{2 \cdot \pi} = 528.48\,kHz$

$g_{mm} := \frac{I_m}{V_T}$ $\quad g_{mm} = 0.407\,\frac{mA}{V}$

$A_m := g_{mm} \cdot R_{1m}$ $\quad A_m = 58.189$

$A_{maxm} := \frac{1}{\left(\frac{1}{Q} \cdot \frac{\omega_0}{\omega_{1m}} + g_{mm} \cdot R_{1m}\right)}$ $\quad 20 \cdot \log\left(\left|A_{maxm}\right|\right) = -35.538\,dB$ Maximum Attenuation with a fast transistor

$f_{notchm} := \frac{\omega_0}{2 \cdot \pi} \cdot \sqrt{A_m}$ $\quad f_{notchm} = 4.68\,MHz$ Frequency of the Notch

$A_{notchm} := \frac{1}{A_m}$ $\quad 20 \cdot \log\left(A_{notchm}\right) = -35.297\,dB$ Depth of Notch

$area_{Rm} := W_{min} \cdot \frac{\left(R_{1m} + R_{2m}\right) \cdot W_{min}}{R_{sq}}$ $\quad \sqrt{area_{Rm}} = 13.52\,\mu m$

$cost_{Rm} := cost\_mm2 \cdot area_{Rm}$ $\quad cost_{Rm} = 2.194 \times 10^{-3}\,cent$

$area_{Cm} := \frac{1}{C\_area} \cdot \left(C_{1m} + C_{2m}\right)$ $\quad \sqrt{area_{Cm}} = 66.665\,\mu m$

$cost_{Cm} := cost\_mm2 \cdot area_{Cm}$ $\quad cost_{Cm} = 0.053\,cent$

$area_m := area_{Cm} + area_{Rm}$ $\quad \sqrt{area_m} = 68.022\,\mu m$

$cost_{powerm} := cost_{power} \cdot I_m \cdot V_{DD}$ $\quad cost_{powerm} = 0.081\,cent$

$cost_m := cost_{Cm} + cost_{Rm} + cost_{powerm}$ $\quad cost_m = 0.136\,cent$

Solving Assumption #4.5: Other Solution to Quadratic of 4.

$C_{1m2} := C_{maxm} \cdot 1.05$ $\quad C_{1m2} = 2.107\,pF$

$valid_{m2} := Q < \omega_0 \cdot C_{1m2} \cdot \left(\frac{V_{neq}^{2} - V_n^{2}}{4 \cdot k \cdot Temp \cdot 4}\right)$ $\quad valid_{m2} = 1$

$R_{2m2} := \frac{V_{neq}^{2} - V_n^{2}}{4 \cdot k \cdot Temp \cdot 2} \cdot \left[1 - \sqrt{1 - \frac{(4 \cdot k \cdot Temp) \cdot 4}{\left(V_{neq}^{2} - V_n^{2}\right)} \cdot \frac{Q}{\omega_0 \cdot C_{1m2}}}\right]$ $\quad R_{2m2} = 142.905\,k\Omega$

$R_{1m2} := \frac{V_{neq}^{2} - V_n^{2}}{4 \cdot k \cdot Temp} - R_{2m2}$ $\quad R_{1m2} = 222.683\,k\Omega$

$C_{2m2} := \frac{1}{\omega_0^{2} \cdot R_{1m2} \cdot R_{2m2} \cdot C_{1m2}}$ $\quad C_{2m2} = 1.004\,pF$

$\omega_{0m2} := \frac{1}{\sqrt{R_{1m2} \cdot R_{2m2} \cdot C_{1m2} \cdot C_{2m2}}}$ $\quad \frac{\omega_{0m2}}{2 \cdot \pi} = 613.5\,kHz$

$Q_{m2} := \frac{\omega_0}{\frac{1}{R_{1m2} \cdot C_{1m2}} + \frac{1}{R_{2m2} \cdot C_{1m2}} + \frac{1 - G}{R_{2m2} \cdot C_{2m2}}}$ $\quad Q_{m2} = 0.707$

$[\ldots] := \omega_0 \cdot C \ldots \left(V_{neq}^{2} - V_n^{2}\right) \ldots$

$Q_{maxm2} := \omega_0 \cdot C_{1m2} \cdot \left(\frac{\ldots}{4 \cdot k \cdot Temp \cdot 4} \right)$ $\qquad Q_{maxm2} = 0.742$

$C_{Leff} := C_{1m2}$ $\qquad C_{Leff} = 2.107\,pF$ Estimated Load Capacitance

$I_{slewm2} := C_{Leff} \cdot \Delta Voutswing\_\Delta t$ $\qquad I_{slewm2} = 10.546\,\mu A$ Required Current to Slew Output

$$I_{noisem2} := \frac{\left[4 \cdot k \cdot Temp \cdot \left(\frac{V_T}{2} \right) \right]}{V_n^{\,2}}$$ $\qquad I_{noisem2} = 0.106\,\mu A$

$I_{m2} := \text{if}\left(I_{slewm2} > I_{noisem2}, I_{slewm2}, I_{noisem2}\right)$

$I_{m2} := \text{if}\left(I_{m2} < I_{min}, I_{min}, I_{m2}\right)$ $\qquad I_{m2} = 10.546\,\mu A$

$$\omega_{1m2} := \frac{1}{R_{1m2} \cdot C_{1m2}} \qquad \frac{\omega_{1m2}}{2 \cdot \pi} = 339.148\,kHz$$

$$g_{mm2} := \frac{I_{m2}}{V_T} \qquad g_{mm2} = 0.407\,\frac{mA}{V}$$

$A_{m2} := g_{mm2} \cdot R_{1m2}$ $\qquad A_{m2} = 90.673$

$$A_{maxm2} := \frac{1}{\left(\frac{1}{Q} \cdot \frac{\omega_0}{\omega_{1m2}} + g_{mm2} \cdot R_{1m2} \right)} \qquad 20 \cdot \log\left(\left| A_{maxm2} \right| \right) = -39.391\,dB$$

Maximum Attenuation with a fast transistor

$$f_{notchm2} := \frac{\omega_0}{2 \cdot \pi} \cdot 2\sqrt{A_m} \qquad f_{notchm2} = 9.36\,MHz$$

Frequency of the Notch

$$A_{notchm2} := \frac{1}{A_{m2}} \qquad 20 \cdot \log\left(A_{notchm2}\right) = -39.15\,dB$$

Depth of Notch

$$area_{Rm2} := W_{min} \cdot \frac{\left(R_{1m2} + R_{2m2}\right) \cdot W_{min}}{R_{sq}} \qquad \sqrt{area_{Rm2}} = 13.52\,\mu m$$

$cost_{Rm2} := cost\_mm2 \cdot area_{Rm2}$ $\qquad cost_{Rm2} = 2.194 \times 10^{-3}\,cent$

$$area_{Cm2} := \frac{1}{C\_area} \cdot \left(C_{1m2} + C_{2m2}\right) \qquad \sqrt{area_{Cm2}} = 66.665\,\mu m$$

$cost_{Cm2} := cost\_mm2 \cdot area_{Cm2}$ $\qquad cost_{Cm2} = 0.053\,cent$

$area_{m2} := area_{Cm2} + area_{Rm2}$ $\qquad \sqrt{area_{m2}} = 68.022\,\mu m$

$cost_{powerm2} := cost_{power} \cdot I_{m2} \cdot V_{DD}$ $\qquad cost_{powerm2} = 0.081\,cent$

$cost_{m2} := cost_{Cm2} + cost_{Rm2} + cost_{powerm2}$ $\qquad cost_{m2} = 0.136\,cent$

Solving Assumption #5: $R_1 = R_{max}$

$$R_{max} := \frac{cost_{Rext}}{cost\_mm2} \cdot \frac{R_{sq}}{W_{min}^{\,2}} \qquad R_{max} = 442.267\,M\Omega$$

$R_{max} := \text{if}\left(R_{max} < R_{maxdes}, R_{max}, R_{maxdes}\right)$ $\qquad R_{max} = 400\,k\Omega$

$$Area_{Rmax} := W_{min} \cdot \frac{R_{max} \cdot W_{min}}{R_{sq}} \qquad \sqrt{Area_{Rmax}} = 14.142\,\mu m$$

$R_{1n} := R_{max}$ $\qquad R_{1n} = 400\,k\Omega$

$$R_{2n} := \frac{V_{neq}^{\,2} - V_n^{\,2}}{4 \cdot k \cdot Temp} - R_{1n} \qquad R_{2n} = -34.413\,k\Omega$$

$$C_{1n} := \left(\frac{1}{R_{1n}} + \frac{1}{R_{2n}} \right) \cdot \frac{Q}{\omega_0} \quad \text{if } G = 1$$

$$\left\| \frac{\omega_0}{2\cdot Q}\cdot\frac{1}{\left[(1-G)\cdot\omega_0^{\,2}\cdot R_{1n}\right]}\cdot\left[1-\sqrt{1-\left(1+\frac{R_{1n}}{R_{2n}}\right)\cdot 4\cdot(1-G)\cdot Q^2}\right] \right. \quad \text{if } G \neq 1$$

$C_{1n} = -4.872\,\text{pF}$

$$G_{thresh} := 1-\frac{1}{4\cdot Q^2\cdot\left(1+\frac{R_{1n}}{R_{2n}}\right)}$$ $G_{thresh} = 1.047$

G must be greater than 0.773 for C1 to be real

$valid_n := (G > G_{thresh})\cdot(R_{2n} > 0)$ $valid_n = 0$

$$C_{2n} := \frac{1}{\omega_0^{\,2}\cdot R_{1n}\cdot R_{2n}\cdot C_{1n}}$$ $C_{2n} = 1.004\,\text{pF}$

$$\omega_{0n} := \frac{1}{\sqrt{R_{1n}\cdot R_{2n}\cdot C_{1n}\cdot C_{2n}}}$$ $\frac{\omega_{0n}}{2\cdot\pi} = 613.5\,\text{kHz}$

$$Q_n := \frac{\omega_0}{\frac{1}{R_{1n}\cdot C_{1n}}+\frac{1}{R_{2n}\cdot C_{1n}}+\frac{1-G}{R_{2n}\cdot C_{2n}}}$$ $Q_n = 0.707$

$C_{Leff} := C_{1n}$ $C_{Leff} = -4.872\,\text{pF}$ Estimated Load Capacitance

$I_{slewn} := C_{Leff}\cdot\Delta Voutswing\_\Delta t$ $I_{slewn} = -24.38\,\mu\text{A}$ Required Current to Slew Output

$$I_{noisen} := \frac{\left[4\cdot k\cdot Temp\cdot\left(\frac{V_T}{2}\right)\right]}{V_n^{\,2}}$$ $I_{noisen} = 0.106\,\mu\text{A}$

$I_n := \text{if}(I_{slewn} > I_{noisen}, I_{slewn}, I_{noisen})$

$I_n := \text{if}(I_n < I_{min}, I_{min}, I_n)$ $I_n = 10\,\mu\text{A}$

$$\omega_{1n} := \frac{1}{R_{1n}\cdot C_{1n}}$$ $\frac{\omega_{1n}}{2\cdot\pi} = -81.67\,\text{kHz}$

$$g_{mn} := \frac{I_n}{V_T}$$ $g_{mn} = 0.386\,\frac{\text{mA}}{\text{V}}$

$A_n := g_{mn}\cdot R_{1n}$ $A_n = 154.447$

$$A_{maxn} := \frac{1}{\left(\frac{1}{Q}\cdot\frac{\omega_0}{\omega_{1n}}+g_{mn}\cdot R_{1n}\right)}$$ $20\cdot\log(|A_{maxn}|) = -43.157\,\text{dB}$ Maximum Attenuation with a fast transistor

$$f_{notchn} := \frac{\omega_0}{2\cdot\pi}\cdot\sqrt{A_n}$$ $f_{notchn} = 7.624\,\text{MHz}$ Frequency of the Notch

$$A_{notchn} := \frac{1}{A_n}$$ $20\cdot\log(A_{notchn}) = -43.776\,\text{dB}$ Depth of Notch

$$area_{Rn} := W_{min}\cdot\frac{(R_{1n}+R_{2n})\cdot W_{min}}{R_{sq}}$$ $\sqrt{area_{Rn}} = 13.52\,\mu\text{m}$

$cost_{Rn} := cost\_mm2\cdot area_{Rn}$ $cost_{Rn} = 2.194\times 10^{-3}\,\text{cent}$

$$area_{Cn} := \frac{1}{C\_area}\cdot(C_{1n}+C_{2n})$$ $\sqrt{area_{Cn}} = 74.339i\,\mu\text{m}$

$cost_{Cn} := cost\_mm2\cdot area_{Cn}$ $cost_{Cn} = -0.066\,\text{cent}$

$area_n := area_{Cn} + area_{Rn}$ $\sqrt{area_n} = 73.099i\,\mu\text{m}$

$cost_{powern} := cost_{power}\cdot I_n\cdot V_{DD}$ $cost_{powern} = 0.076\,\text{cent}$

$cost_n := cost_{Cn} + cost_{Rn} + cost_{powern}$ $cost_n = 0.012\,cent$

Solving Assumption #6: Minimize Area

This doesn't work for G<1. It spits out unrealistically sized values for G's close to one. Lets set a threshold of a G of about 1.3. In general the area is dominated by the capacitor

$R_{1g} := 0.6M\Omega$ Guess at R1

$valid_a := G > 1.3$ $valid_a = 0$

$$R_{1a} := root\left[\left(\frac{1}{R_{1g}} + \frac{1}{R_{1g} - \frac{V_{neq}^2 - V_n^2}{4\cdot k\cdot Temp}}\right)\cdot\frac{1}{\frac{W_{min}^2\cdot C\_area}{R_{sq}}\cdot R_{1g}} + (1-G)\cdot R_{1g}^2\cdot\frac{W_{min}^2\cdot C\_area}{R_{sq}}\cdot\omega_0^2 - \frac{Q}{\omega_0}, R_{1g}\right]$$

$R_{1a} = 2.627\times 10^8\,k\Omega$

$$R_{2a} := R_{1a} - \frac{V_{neq}^2 - V_n^2}{4\cdot k\cdot Temp}$$ $R_{2a} = 2.627\times 10^8\,k\Omega$

$$C_{1a} := \frac{W_{min}^2\cdot C\_area}{R_{sq}}\cdot R_{1a}$$ $C_{1a} = 9.194\times 10^4\,pF$

$$C_{2a} := \frac{1}{\left(R_{1a}^2\cdot\frac{W_{min}^2\cdot C\_area}{R_{sq}}\cdot\omega_0^2\right)\cdot R_{2a}}$$ $C_{2a} = 0\,pF$

Outputs

Implementation, where $C_1=C_2=C$

$valid_c = 0$	**Are these Coefficients Valid? 0=no, 1=yes**
$R_{1c} = 182.794 - 182.79i\,k\Omega$	**Resistor 1 Value**
$R_{2c} = 182.794 + 182.79i\,k\Omega$	**Resistor 2 Value**
$C_{1c} = 1.004\,pF$	**Capacitor Value**
$C_{2c} = 1.004\,pF$	**Capacitor Value**
$I_c = 10\,\mu A$	**Required Current to Slew Output**
$20\cdot\log(\lvert A_{maxc}\rvert) = -40.106\,dB$	**Maximum Attenuation with a fast transistor**
$f_{notchc} = 5.663 - 2.346i\,MHz$	**Frequency of the Notch**
$20\cdot\log(A_{notchc}) = -39.984 + 6.822i\,dB$	**Depth of Notch**
$cost_c = 0.113\,cent$	**Cost of c method**

Implementation, where $R_1=R_2=R$

$valid_r = 1$	**Are these Coefficients Valid? 0=no, 1=yes**
$R_{1r} = 100\,k\Omega$	**Resistor 1 Value**
$R_{2r} = 100\,k\Omega$	**Resistor 2 Value**
$C_{1r} = 3.669\,pF$	**Capacitor 1 Value**
$C_{2r} = 1.834\,pF$	**Capacitor 2 Value**
$I_r = 18.359\,\mu A$	**Required Current to Slew Output**
$20\cdot\log(\lvert A_{maxr}\rvert) = -37.253\,dB$	**Maximum Attenuation with a fast transistor**
$f_{notchr} = 5.165\,MHz$	**Frequency of the Notch**
$20\cdot\log(A_{notchr}) = -37.011\,dB$	**Depth of Notch**
$cost_r = 0.236\,cent$	**Cost of r method**

Implementation, where $C_1=C_{max}$.

$valid_m = 1$	**Are these Coefficients Valid? 0=no, 1=yes**
$R_{1m} = 142.905\,k\Omega$	**Resistor 1 Value**
$R_{2m} = 222.683\,k\Omega$	**Resistor 2 Value**
$C_{1m} = 2.107\,pF$	**Capacitor 1 Value**
$C_{2m} = 1.004\,pF$	**Capacitor 2 Value**
$I_m = 10.546\,\mu A$	**Required Current to Slew Output**
$20\cdot\log(\lvert A_{maxm}\rvert) = -35.538\,dB$	**Maximum Attenuation with a fast transistor**
$f_{notchm} = 4.68\,MHz$	**Frequency of the Notch**
$20\cdot\log(A_{notchm}) = -35.297\,dB$	**Depth of Notch**
$cost_m = 0.136\,cent$	**Cost of m method**

2nd Implementation, where $C_1=C_{max}$.

$valid_{m2} = 1$	**Are these Coefficients Valid? 0=no, 1=yes**
$R_{1m2} = 222.683\,k\Omega$	**Resistor 1 Value**
$R_{2m2} = 142.905\,k\Omega$	**Resistor 2 Value**
$C_{1m2} = 2.107\,pF$	**Capacitor 1 Value**
$C_{2m2} = 1.004\,pF$	**Capacitor 2 Value**
$I_{m2} = 10.546\,\mu A$	**Required Current to Slew Output**
$20\cdot\log(\lvert A_{maxm2}\rvert) = -39.391\,dB$	**Maximum Attenuation with a fast transistor**
$f_{notchm2} = 9.36\,MHz$	**Frequency of the Notch**
$20\cdot\log(A_{notchm2}) = -39.15\,dB$	**Depth of Notch**
$cost_{m2} = 0.136\,cent$	**Cost of m2 method**

Implementation, where $R_1=R_{max}$.

$valid_n = 0$	**Are these Coefficients Valid? 0=no, 1=yes**
$R_{1n} = 400\,k\Omega$	**Resistor 1 Value**
$R_{2n} = -34.413\,k\Omega$	**Resistor 2 Value**
$C_{1n} = -4.872\,pF$	**Capacitor 1 Value**
$C_{2n} = 1.004\,pF$	**Capacitor 2 Value**
$I_n = 10\,\mu A$	**Required Current to Slew Output**
$20\cdot\log(\lvert A_{maxn}\rvert) = -43.157\,dB$	**Maximum Attenuation with a fast transistor**
$f_{notchn} = 7.624\,MHz$	**Frequency of the Notch**
$20\cdot\log(A_{notchn}) = -43.776\,dB$	**Depth of Notch**
$cost_n = 0.012\,cent$	**Cost of n method**

$$architecture := \begin{array}{|l} 1 \text{ if } valid_r \\ 2 \text{ if } valid_c \\ 3 \text{ if } valid_m \\ error(\text{"none are valid"}) \text{ if } (1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r) \end{array}$$

$architecture = 3$

$$R_1 := \begin{array}{|l} R_{1r} \text{ if } valid_r \\ R_{1c} \text{ if } valid_c \end{array}$$

R_{1m} if $valid_m$
$error(\text{"none are valid"})\cdot\Omega$ if $(1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r)$

$R_1 = 142.905\,k\Omega$

$$R_2 := \begin{cases} R_{2r} & \text{if } valid_r \\ R_{2c} & \text{if } valid_c \\ R_{2m} & \text{if } valid_m \\ error(\text{"none are valid"})\cdot\Omega & \text{if } (1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r) \end{cases}$$

$R_2 = 222.683\,k\Omega$

$$C_1 := \begin{cases} C_{1r} & \text{if } valid_r \\ C_{1c} & \text{if } valid_c \\ C_{1m} & \text{if } valid_m \\ error(\text{"none are valid"})\cdot F & \text{if } (1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r) \end{cases}$$

$C_1 = 2.107\,pF$

$$C_2 := \begin{cases} C_{2r} & \text{if } valid_r \\ C_{2c} & \text{if } valid_c \\ C_{2m} & \text{if } valid_m \\ error(\text{"none are valid"})\cdot F & \text{if } (1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r) \end{cases}$$

$C_2 = 1.004\,pF$

$$I := \begin{cases} I_r & \text{if } valid_r \\ I_c & \text{if } valid_c \\ I_m & \text{if } valid_m \\ error(\text{"none are valid"})\cdot A & \text{if } (1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r) \end{cases}$$

$I = 0.011\,mA$

$$A_{max} := \begin{cases} A_{maxr} & \text{if } valid_r \\ A_{maxc} & \text{if } valid_c \\ A_{maxm} & \text{if } valid_m \\ error(\text{"none are valid"}) & \text{if } (1-valid_m)\cdot(1-valid_c)\cdot(1-valid_r) \end{cases}$$

$20\cdot\log(|A_{max}|) = -35.538\,dB$

$g_m := \frac{I}{V_T}$ $\qquad g_m = 0.407\,\frac{mA}{V}$

$A := g_m\cdot R_1$ $\qquad A = 58.189$

$$f_{notch} := \frac{\omega_0}{(2\cdot\omega_1)}\cdot\left[-1+\sqrt{1+4\cdot\left(\frac{\omega_1}{\omega_0}\right)^2\cdot A}\right]\cdot\frac{\omega_0}{2\cdot\pi}$$

$f_{notch} = \blacksquare\ MHz$ $\qquad$ Useful bandwidth

$f_{notchguess} := \sqrt{A}\cdot\frac{\omega_0}{2\cdot\pi}$ $\qquad f_{notchguess} = 4.68\,MHz$

$A_{notch} := 20\cdot\log(|A_1(A,\omega_1,j\cdot 2\cdot\pi\cdot f_{notch})|)$ $\qquad A_{notch} = \blacksquare\ dB$

$A_{jammer} := 20\cdot\log(|A_1(A,\omega_1,j\cdot 2\cdot\pi\cdot f_{jammer})|)$ $\qquad A_{jammer} = \blacksquare\ dB$

$20\cdot\log(|A_1(A,\omega_1,j\cdot 2\cdot\pi\cdot f_{notchguess})|) = \blacksquare\ dB$

$$f_{start} := \frac{f_0}{10}$$ Starting Frequency for Plotting

$$f_{stop} := f_0 \cdot 100$$ Stopping Frequency for Plotting

$$f_i := \left(\frac{f_{stop}}{f_{start}}\right)^{\frac{i}{num}} \cdot f_{start} \qquad \omega_i := 2 \cdot \pi \cdot f_i \qquad s_i := j \cdot \omega_i$$

Filter Response vs. Frequency

744×10^−4

A_{jammer}

Attenuation (dB)

$(|A_{max}|)$

− 80

Frequency (MHz)

$\frac{f_{start}}{MHz}$ $\frac{f_{jammer}}{MHz}$ $\frac{f_{notch}}{MHz}$ $\frac{f_{stop}}{MHz}$

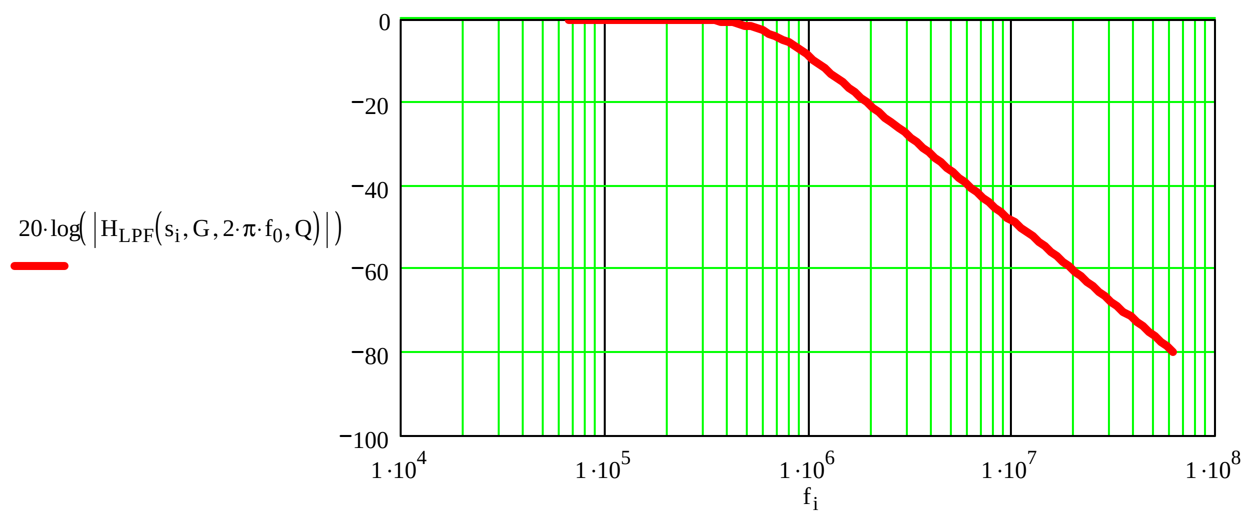
Functions

$$\text{sallenkey}(f_0, Q, SNR, G) := \left| \begin{array}{l}
\text{errval} \leftarrow \text{if}\left[\left(G > \frac{1}{8 \cdot Q^2} + 1\right) \cdot \left(G < 1 + \frac{1}{Q} - \frac{1}{2 \cdot Q^2}\right), 1, 0\right] \\
\text{choice} \leftarrow \text{if}\left(G < \frac{1}{8 \cdot Q^2} + 1, 0, 1\right) \\
R_1 \leftarrow \text{if}\left[\text{choice}, \left[\frac{\frac{1}{2} - Q^2 \cdot (1-G)}{(1-G)^2 \cdot Q^2 + 1}\right] \cdot \frac{V_{neq}^2 - V_n^2}{4 \cdot k \cdot Temp} \cdot \left[1 - \sqrt{1 - \frac{1}{\left[\frac{1}{2 \cdot Q} - Q \cdot (1-G)\right]^2}}\right], \frac{V_{neq}^2 - V_n^2}{2 \cdot 4 \cdot k \cdot Temp}\right] \\
\text{if}(R_1 > R_{max}, R_{max}, R_1) \\
R_2 \leftarrow \text{if}\left(\text{choice}, \frac{V_{neq}^2 - V_n^2}{4 \cdot k \cdot Temp} - R_1, R_1\right) \\
C_2 \leftarrow \text{if}\left[\text{choice}, \frac{1}{\left[R_1 + R_2 + (1-G) \cdot R_1\right] \cdot Q \cdot \omega_0}, \frac{1 + \sqrt{\left[1 - 8 \cdot Q^2 \cdot (G-1)\right]}}{4 \cdot Q \cdot \omega_0 \cdot R}\right] \\
C_1 \leftarrow \text{if}\left[\text{choice}, \frac{1}{\left[R_1 + R_2 + (1-G) \cdot R_1\right] \cdot Q \cdot \omega_0}, \frac{1}{\omega_0^2 \cdot R^2 \cdot C_2}\right] \\
\left(\begin{array}{c} \text{errval} \\ \frac{R_1}{\Omega} \\ R_2 \end{array} \right.
\end{array} \right.$$

$$\begin{pmatrix} \frac{R_2}{\Omega} \\ \frac{C_1}{F} \\ \frac{C_2}{F} \end{pmatrix}$$

Example

$f_0 = 613.5\,kHz$		Center Frequency
$Q = 0.707$		Desired Q
$SNR = 80$		Minimum Signal to Noise Ratio
$G = 1$		Gain
$x := sallenkey(f_0, Q, SNR, G)$		
$errval := x_1$	$errval = 0$	Error? (0=error, 1=no error)
$R_1 := x_2 \cdot \Omega$	$R_1 = 182.794\,k\Omega$	Resistor 1 Value
$R_2 := x_3 \cdot \Omega$	$R_2 = 182.794\,k\Omega$	Resistor 2 Value
$C_1 := x_4 \cdot F$	$C_1 = 3.669\,pF$	Capacitor 1 Value
$C_2 := x_5 \cdot F$	$C_2 = 1.834\,pF$	Capacitor 2 Value

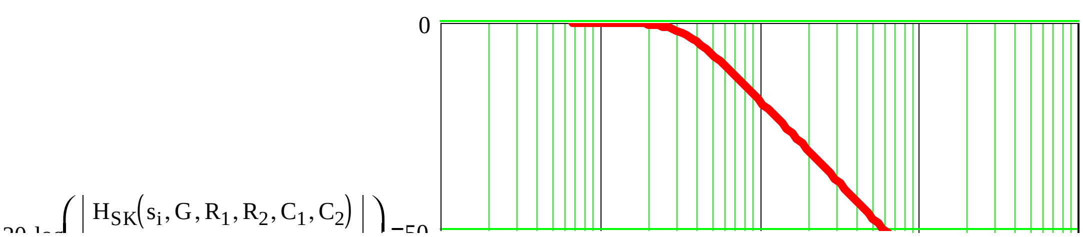


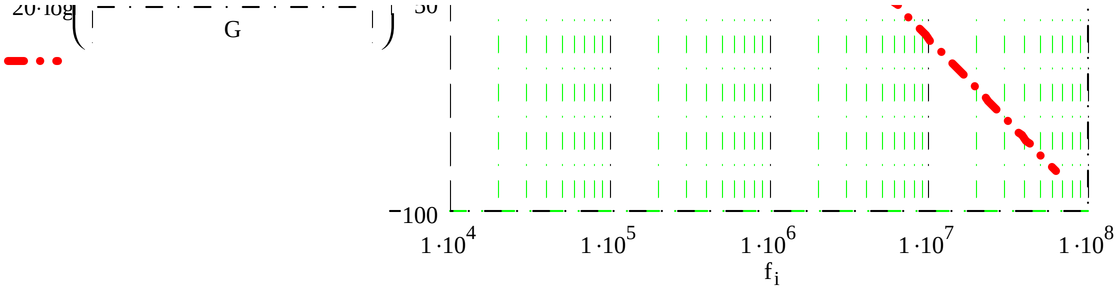
Analysis yields:

$$\omega_0(R_1, R_2, C_1, C_2) := \frac{1}{\sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}} \qquad \frac{\omega_0(R_1, R_2, C_1, C_2)}{2 \cdot \pi} = 0.336\,MHz \qquad \omega_0 = \frac{1}{\sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}}$$

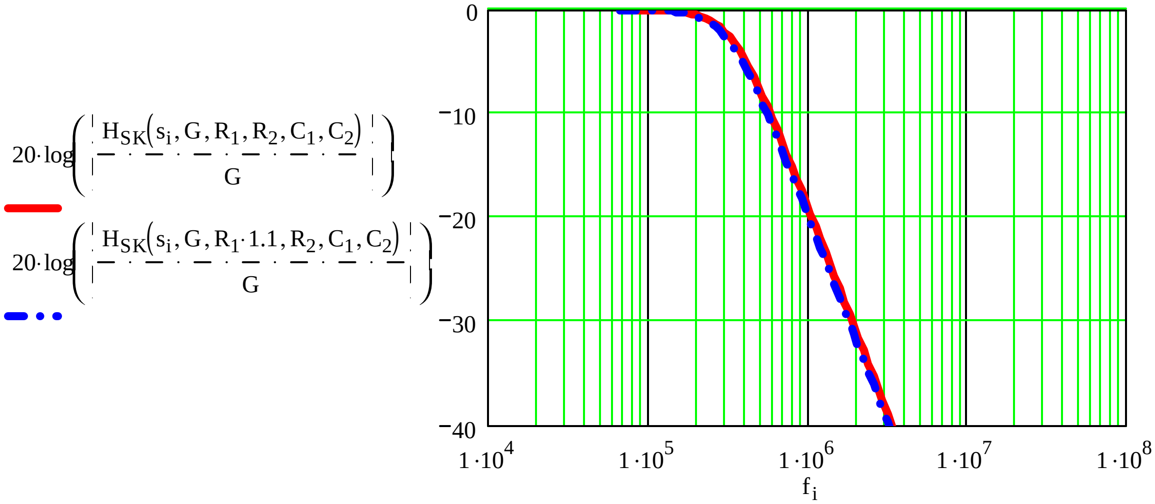
$$Q(G, R_1, R_2, C_1, C_2) := \frac{\frac{1}{\sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}}}{\frac{1}{R_1 \cdot C_1} + \frac{1}{R_2 \cdot C_1} + \frac{1 - G}{R_2 \cdot C_2}} \qquad Q(G, R_1, R_2, C_1, C_2) = 0.707 \qquad Q = \sqrt{\frac{C_1}{C_2}} \cdot \frac{\sqrt{R_1 \cdot R_2}}{R_1 + R_2} = \frac{1}{C_2 \cdot \omega_0 \cdot (R_1 + R_2)}$$

$$H_{SK}(s, G, R_1, R_2, C_1, C_2) := H_{LPF}(s, G, \omega_0(R_1, R_2, C_1, C_2), Q(G, R_1, R_2, C_1, C_2))$$





"small" variations



$$\frac{Q(G, 1.1 \cdot R_1, R_2, C_1, C_2)}{Q(G, R_1, R_2, C_1, C_2)} - 1 = -1.134 \times 10^{-3} \qquad \frac{\omega_0(1.1 \cdot R_1, R_2, C_1, C_2)}{\omega_0(R_1, R_2, C_1, C_2)} - 1 = -0.047$$

Sensitivity

Version 1: $S_{QR1}(Q) := Q - \frac{1}{2}$ $\qquad S_{QR1}(5) = 4.5$

$\Delta R_1 := 0.1 \cdot R_1 \qquad \Delta QbyQ := S_{QR1}(5) \cdot \frac{\Delta R_1}{R_1} \qquad \Delta QbyQ = 0.45$

Version 2: $S_{QR1}(Q) := 0$

Note: true only for very small variations ... large (e.g. 10%) changes of R_1 will still change Q.

Conclusions

choose G=1 for minimum sensitivity!

Other benefits of G=1:
- simplicity, low sensitivity of G ...
- good linearity: voltage accross R is zero in passband

Other Problems:

- sensitive to top/bottom plate parasitics
- sensitive to RC time constant variations

Use only in non-critical applications:
- low pole Q (hence restrict order to 4 or so)
- where large variations of cutoff frequency can be accepted
  (typical variation of untrimmed RC time constants: +/- 30%)

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