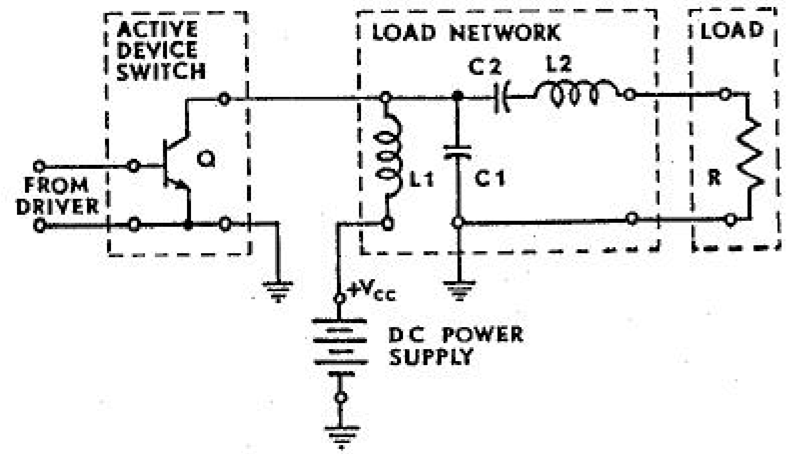


434MHz design sheet 10dBm, on the Reference Board

LoPSTer Class-E PA design sheet

This sheet calculates the components for a class-E PA used on LoPSTer.

The class-E design equations are from "N O Sokal, IEEE MTT-S Digest, Class E switching mode high efficiency PA, Improved Design Equations", 2000.

Other equations are either from Pozar "Microwave Engineering", or the Circuit Sage website. The conversion from ABCD to S21 is done with reference to Dean Frickley, MTT Feb 1994, "Conversion between S and ABCD valid for complex impedances"

Use the Design Procedure section on page 4.

You then have a choice of four matching networks for Rload<50 ohms (matching 1 to 4) and four matching networks for Rload>50 ohms (matching 5 to 8). The component values, output power & harmonics are calculated for each of the circuit topologies.

Chris Haji-Michael

Inputs yellow, outputs green

$mW \equiv \frac{W}{1000}$ $\quad nH \equiv \frac{\mu H}{1000}$

First Calculate C1

C1_total is the total capacitance at C1 and is made up of several capacitance. It includes the PCB capacitance measured using an impedance analyser on a blank board. Here, this is **multiplied by 1.4** to allow for extra stray capacitance when components are soldered. (refer: chap_12_general_information/CustomerSupport/2008-01-04,Fuba_RX_868MHz.pdf). Add to this the LoPSTer output capacitance, C1 and the capacitance for L1.

Finally, L1 backs-off this capacitance to give an effective C1 (C1_eff) which is used in the calculation for load impedance. This adjustment comes from Sokal and in his equations was added to give C1 which here I have called C1_total. Because I am starting with C1_total and doing things in reverse his adjustment is substracted to give C1_eff used in his equations.

$$C_{L1} := \frac{1}{L1\cdot(2\cdot\pi\cdot SRFL1)^2} \qquad C1\_total := C_{pcb1}\cdot 1.4 + C_{lopster} + C_{L1} + C1$$

$$Zc := \frac{1}{2\cdot\pi\cdot freq\cdot C1\_total} \qquad L1\_suggest := \frac{4\cdot Zc}{2\cdot\pi\cdot freq} \qquad C1\_eff := C1\_total - \frac{0.7}{(2\cdot\pi\cdot freq)^2\cdot L1}$$

$C_{L1} = 0.069\,pF$

$C1\_total = 2.651\,pF$

$C1\_eff = 2.128\,pF$

$Zc = 138.341\,ohm$

Calculate Vo and ON-resistance

Some of this comes from the Sokal paper. Icc is the average current taken in the drain of the switching transitors and causes a voltage drop across the inductor L1 and the transistor R and L. The voltage across the FET on-resistance is used to clacluate Vo as 2*Icc*Ron.. The factor of 2 is used because the transistor is only switched-on half the time. The voltage drop across inductor L1 is calculated with 1*Icc.

$$Icc := \frac{Pout\_guess}{Vcc \cdot Eff} \qquad Vcc\_eff := Vcc - ESRL1 \cdot Icc \qquad Z_{Tran\_L} := 2 \cdot \pi \cdot freq \cdot Tran\_L$$

$$V_{Lon} := Z_{Tran\_L} \cdot Icc \cdot 2 \qquad V_{Ron} := Tran\_R \cdot Icc \cdot 2 \qquad V_o := V_{Lon} + V_{Ron}$$

Vo is the saturation voltage

$$Vcc\_eff = 1.488\,V$$

$$Tran\_R\_proposed(V_{Ron}) := \left[12.4985 \cdot \left(\frac{V_{Ron}}{V}\right)^2 - 0.136113 \cdot \frac{V_{Ron}}{V} + 9.42926\right] ohm$$

From simulations of RON with drain-voltage under dc conditions. This is with ACOM=31.

$$V_{Ron} = 0.212\,V$$

$$V_o = 0.247\,V$$

$$Tran\_R\_proposed(V_{Ron}) = 9.961\,ohm$$

Calculate the LoPSTer capacitance

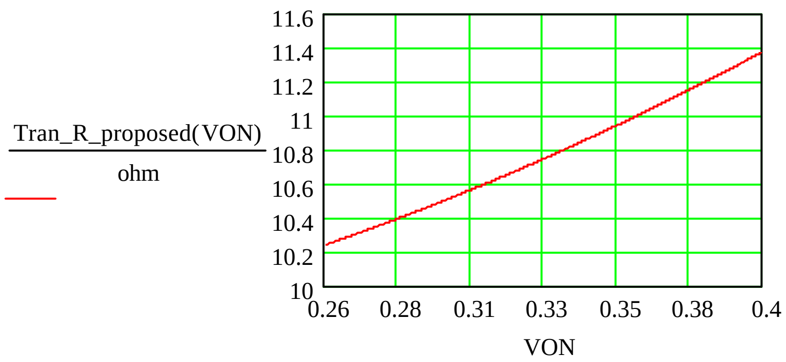
The lopster capacitance varies greatly with drain voltage. The capacitance is important to know at the drain voltage when the transistor switches-on (Voff).

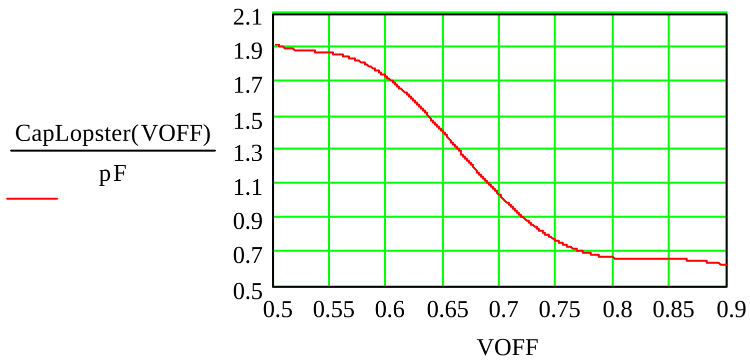
$$V_o = 0.247\,V \qquad Vpeak := 2 \cdot Vcc\_eff \qquad Voff := V_o + (Vpeak - V_o) \cdot 0.2$$

$$CapLopster(Voff) := \left[8627.9 \cdot \left(\frac{Voff}{V}\right)^6 - 38102\left(\frac{Voff}{V}\right)^5 + 69153.1\left(\frac{Voff}{V}\right)^4 - 65955.2\left(\frac{Voff}{V}\right)^3 + 34836.2\left(\frac{Voff}{V}\right)^2 - 9660.4\left(\frac{Voff}{V}\right) + 1101.28\right] \cdot pF$$

$$Voff = 0.792\,V$$

$$CapLopster(Voff) = 0.67\,pF$$





Regulator Output Voltage

$$\text{VCC\_REG(Icc)} := \left[-7.6\cdot 10^{-7}\left(\frac{\text{Icc}}{\text{mA}}\right)^3 + 4.8\cdot 10^{-5}\left(\frac{\text{Icc}}{\text{mA}}\right)^2 - 0.00164\cdot\left(\frac{\text{Icc}}{\text{mA}}\right) + 1.5219\right]\text{V}$$

This is the PA regulator output voltage for PAM0 which varies with load

$\text{Icc} = 10.632\,\text{mA}$

$\text{VCC\_REG(Icc)} = 1.509\,\text{V}$

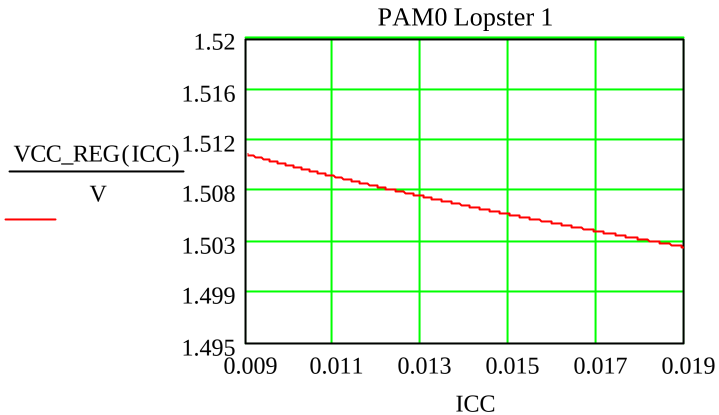
Duty Cycle

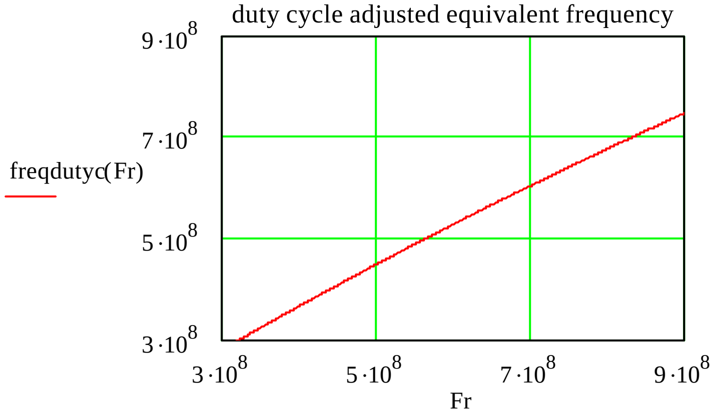
$$\text{dutyc(freq)} := 1.001906 + 0.0004526\left(\frac{\text{freq}}{1\times 10^6\cdot\text{Hz}}\right) \qquad \text{freqdutyc(freq)} := \frac{\text{freq}}{\left(\frac{\text{dutyc(freq)} + 1}{2}\right)}$$

The duty cycle is defined as the off/on ratio and this affects the frequency of the series tuned circuit

$\text{dutyc(freq)} = 1.198$

$\text{freqdutyc(freq)} = 394.844\,\text{MHz}$





Sokal's equations

$$R_{load} := \frac{1}{(34.222 \cdot freqdutyc(freq) \cdot C1\_eff)} \cdot \left(0.99836 + \frac{0.91394}{Q_L} - \frac{1.0316}{Q_L^{\ 2}}\right)$$

Rload here is calculated from equation 5 [Sokal]. This equation is modified as the effect of L1 on C1 has already been compensated for above and then re-arranged.

$$L_2 := \frac{Q_L \cdot R_{load}}{2 \cdot \pi \cdot freqdutyc(freq)} - L_{pcb} - L_{lopster}$$

L2 here is the actual inductor value as if it were a physical component and is reduced by Lpcb and Llopster

$$C_2 := \frac{1}{\left(2 \cdot \pi \cdot freqdutyc(freq) \cdot R_{load}\right)} \cdot \frac{1}{\left(Q_L - 0.1048\right)} \cdot \left[1.0012 + \frac{1.0147}{\left(Q_L - 1.7979\right)}\right]$$

$$Pout\_ideal := \frac{\left(Vcc\_eff - V_o\right)^2}{R_{load}} \cdot 0.576801 \cdot \left(1.0012 - \frac{0.4517}{Q_L} - \frac{0.4024}{Q_L^{\ 2}}\right)$$

$$Pout\_real := \frac{\left(Vcc\_eff - V_o\right)^2}{R_{load} + 1.365 \cdot Tran\_R + ESRL2} \cdot 0.576801 \cdot \left(1.0012 - \frac{0.4517}{Q_L} - \frac{0.4024}{Q_L^{\ 2}}\right)$$

Account for real losses by taking into account the Transistor on-resistance, Transistor source inductance and the ESR of L2. This is modified to include the impedance of the source inductor. Otherwise this is directly from the reference.

Efficiency

$$Efficiency := 1 - \left(\frac{\dfrac{Tran\_R\_proposed\left(V_{Ron}\right)}{1.36}}{R_{load} + \dfrac{Tran\_R\_proposed\left(V_{Ron}\right)}{1.36}}\right)$$

This is derived from simulations of an ideal amplifier

$Efficiency = 0.848$

Design Procedure

Step 1.

Enter these values. Lpcb is the effective inductance of the pcb from the output pin of Lopster to Rload. Cpcb is on the ouput pin of Lopster to gnd. Cpcb2 is between L2 & C2

These are the only PCB parasitics considered in the design.

=>

$freq \equiv 434 \cdot MHz$ $C1 \equiv 1pF$ $L_{lopster} \equiv 1.8nH$

$L_{pcb} \equiv 5nH$ $C_{pcb1} \equiv 0.580pF$ $CapPackage \equiv 0.1pF$

$C_{pcb2} \equiv 0.240pF$ $Tran\_L \equiv 0.6nH$

$C_{pcb3} \equiv 0.280pF$

Step 2.

Set VCC

$VCC\_REG(Icc) = 1.509\,V$ => $Vcc \equiv 1.509V$

Step 3.

Set the lopster capacitance. Add 100fF for package.

$CapLopster(Voff) + CapPackage = 0.77\,pF$ => $C_{lopster} \equiv 0.77pF$

Step 4.

The on-resistance of the PA transistors and simulations show that this changes for ACON and the voltage across the transistors.

$Icc = 10.632\,mA$

$V_{Ron} = 0.212\,V$

$Tran\_R\_proposed(V_{Ron}) = 9.961\,ohm$ => $Tran\_R \equiv 9.961 \cdot ohm$

Step 5.

From the suggested L1 select the real L1 with its self resonance and ESR. Use a LQW18 high performance 0603 component series from Murata as these have less loss.

Note: use SRF = 1.1 x spec limit SRF
use ESR = 0.9 x spec limit ESR

$L1\_suggest = 202.928\,nH$ =>

$L1 \equiv 180nH$

$SRFL1 \equiv 1.3 \bullet 1.1 \cdot GHz$

$ESRL1 \equiv 2.2 \bullet 0.9 \cdot ohm$

$Pout\_ideal = 18.207\,mW$

Step 6.

Adjust the Pout_guess until the two values converge.

$Pout\_real = 13.6\,mW$ => $Pout\_guess \equiv 13.605mW$

Step 7.

Adjust QL to get a good value for C2. QL must be greater than 1.8.

$Q_L \equiv 3.474$ => $C_2 = 4.699\,pF$

Step 8.

The PCB inductance is already substracted and from L2 and so get the SRF and ESR assuming LQW15 or LQW18 high performance 0402. (This as component may not actually be used so choose data for the nearest equivalent)

$L_2 = 50.47\,nH$ => $SRFL2 \equiv 2.7 \bullet 1.1 \cdot GHz$

$ESRL2 \equiv 0.29 \bullet 0.9 \cdot ohm$

Note: use SRF = 1.1 x spec limit SRF
use ESR = 0.9 x spec limit ESR

Step 9.

From the calculated efficiency put Eff. This has a secondary effect on the RON and the voltage across the transistors.

$Efficiency = 0.848$ => $Eff \equiv 0.848$

AT THIS POINT REPEAT FROM STEP 1 UNTIL CONVERGENCE

Step 10.

These values affect the added LPF. FR is the ratio of the filter cutoff frequency to the output frequency and should be selected to have the minimum loss at the required frequency. Lar_db is the filter ripple. A higher ripple reduces the harmonics, but also increases the losses.

$FR \equiv 1.17$ $L_{ar\_db} \equiv 2.4$

Step 11

The notch_ratio defines the notch, too low and the notch is too wide, too high and the impedance at the wanted frequency changes too much. Suggest 1.2 to 1.6. Default 1.40

$notch\_ratio \equiv 1.4$

Step 12.

If Rload is < 50 Ohms then goto matching 1 to 4.
If Rload is > 50 Ohms then goto matching 5 to 8

$R_{load} = 40.9\,ohm$

Design the Impedance Match to 50 Ohms, when Rload > 50 Ohms

These equations are for Rload greater than 50 ohms, with the match following the series LC. The starting component is a capacitor to gnd at Rload, followed by a series inductor at 50 ohms.

$$Q_{match} := \sqrt{\frac{R_{load}}{50\cdot ohm} - 1} \qquad C_{gnd\_1} := \frac{Q_{match}}{2\cdot\pi\cdot freq\cdot R_{load}} \qquad L_{series\_1} := \frac{Q_{match}\cdot 50\cdot ohm}{2\cdot\pi freq}$$

$Q_{match} = 0.427i$ $C_{gnd\_1} = 3.825i\,pF$ $L_{series\_1} = 7.822i\,nH$

Design the Impedance Match to 50 Ohms, when Rload < 50 Ohms

These equations are for Rload less than 50 ohms.

The series inductor at Rload will be added to the resonant L, the capacitor to gnd is at 50 ohms

$$Q_{match} := \sqrt{\frac{50\cdot ohm}{R_{load}} - 1} \qquad L_{series\_2} := \frac{Q_{match}\cdot R_{load}}{2\cdot\pi freq} \qquad C_{gnd\_2} := \frac{Q_{match}}{2\cdot\pi\cdot freq\cdot 50\cdot ohm}$$

$$L_{series\_modified\_2} := L_2 + L_{series\_2}$$

$Q_{match} = 0.472$ $L_{series\_2} = 7.075\,nH$ $C_{gnd\_2} = 3.46\,pF$

Note both the IC and the pcb has inductance which has already been substracted.

Add a further PI section filter if required

This is to add a further LC pole to remove harmonics. This value is the cutoff ratio **FR * freq** and is set for 15%. This is the ratio of the third order Tchebychev peak to the Fc of the filter.

When Rload>50 ohm, a three stage filter is proposed starting with series L.

when Rload<50 ohm, a three stage filter is proposed starting with cap to ground.

$$L_{g1} := \frac{50\cdot ohm\cdot g_1}{2\cdot\pi\cdot FR\cdot freq} \qquad C_{g2} := \frac{g_2}{50\cdot ohm\cdot 2\cdot\pi\cdot FR\cdot freq} \qquad L_{g3} := \frac{50\cdot ohm\cdot g_3}{2\cdot\pi\cdot FR\cdot freq}$$

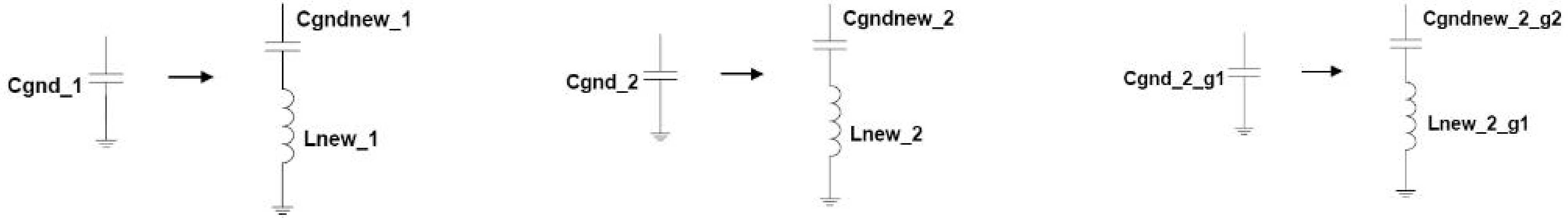
$$L_{series\_modified\_1} := L_{series\_1} + L_{g1}$$

$L_{series\_modified\_1} = 46.502 + 7.822i\,nH$ $C_{g2} = 4.893\,pF$ $L_{g3} = 46.502\,nH$

$$C_{g1} := \frac{g_1}{50\cdot ohm\cdot 2\cdot\pi\cdot FR\cdot freq} \qquad L_{g2} := \frac{50\cdot ohm\cdot g_2}{2\cdot\pi\cdot FR\cdot freq} \qquad C_{g3} := \frac{g_3}{50\cdot ohm\cdot 2\cdot\pi\cdot FR\cdot freq}$$

$C_{g1} = 18.601\,pF$ $L_{g2} = 12.232\,nH$ $C_{g3} = 18.601\,pF$

Make the first capacitor into a notch for the three possible designs.



The capacitor to ground can be replaced by a notch to target the second harmonic which is usually quite high in a class-E amplifier. The Q of the notch is set by the notch_ratio, a low number is very selective and component tolerances may mistune this to have little effect. A high number is a broader notch with that will give less-peak attenuation. The ratio of 1.4 is about right for most applications.

Convert the capacitor to ground (Cgnd) to a series LC notch to attenuate the second harmonic, when Rload > 50 Ohms

$C_{gndnew\_1} := \dfrac{C_{gnd\_1}}{notch\_ratio}$ $\quad Z_{now\_1} := \dfrac{1}{2\cdot\pi\cdot freq\cdot C_{gnd\_1}}$ $\quad L_{new\_1} := \dfrac{1}{(4\cdot\pi\cdot freq)^2\cdot C_{gndnew\_1}}$ $\quad Z_{new\_1} := \dfrac{1}{2\cdot\pi\cdot freq\cdot C_{gndnew\_1}} - 2\cdot\pi\cdot freq\cdot L_{new\_1}$

$C_{gnd\_1} = 3.825i\,pF$ **=>** $C_{gndnew\_1} = 2.732i\,pF$ $\quad Z_{now\_1} = -95.872i\,ohm$

$L_{new\_1} = -12.305i\,nH$ $\quad Z_{new\_1} = -100.665i\,ohm$

Convert the capacitor to ground (Cgnd) to a series LC notch to attenuate the second harmonic, when Rload < 50 Ohms

$$C_{gndnew\_2} := \frac{C_{gnd\_2}}{notch\_ratio} \qquad Z_{now\_2} := \frac{1}{2\cdot\pi\cdot freq\cdot C_{gnd\_2}} \qquad L_{new\_2} := \frac{1}{(4\cdot\pi\cdot freq)^2\cdot C_{gndnew\_2}} \qquad Z_{new\_2} := \frac{1}{2\cdot\pi\cdot freq\cdot C_{gndnew\_2}} - 2\cdot\pi\cdot freq\cdot L_{new\_2}$$

$C_{gnd\_2} = 3.46\,pF$ **=>** $C_{gndnew\_2} = 2.471\,pF$ $Z_{now\_2} = 106.002\,ohm$

$L_{new\_2} = 13.605\,nH$ $Z_{new\_2} = 111.302\,ohm$

Convert the capacitor to ground (Cgnd+Cg1) to a series LC notch to attenuate the second harmonic, when Rload < 50 Ohms.

$$C_{gnd\_2\_g1} := C_{gnd\_2} + C_{g1} \qquad C_{gndnew\_2\_g1} := \frac{C_{gnd\_2\_g1}}{notch\_ratio} \qquad Z_{now\_3} := \frac{1}{2\cdot\pi\cdot freq\cdot\left(C_{gnd\_2} + C_{g1}\right)} \qquad L_{new\_2\_g1} := \frac{1}{(4\cdot\pi\cdot freq)^2\cdot C_{gndnew\_2\_g1}}$$

$$Z_{new\_3} := \frac{1}{2\cdot\pi\cdot freq\cdot C_{gndnew\_2\_g1}} - 2\cdot\pi\cdot freq\cdot L_{new\_2\_g1}$$

$C_{gnd\_2\_g1} = 22.06\,pF$ **=>** $C_{gndnew\_2\_g1} = 15.757\,pF$ $Z_{now\_3} = 16.623\,ohm$

$L_{new\_2\_g1} = 2.134\,nH$ $Z_{new\_3} = 17.454\,ohm$

Calculate Harmonics out of the class-E tuned network

These harmonics (-dBc) are out of the series LC tuned network. They are calculated according to N O Sokal, F H Raab, Harmonic output of class E PA and load coupling network design JSSC Feb 1977. These equations are modified according to N O Sokal "Improved Design Equations", last paragraph.

$$I_n/I_1 \approx (c_n/c_1)(Z_1/Z_n) \qquad (1)$$

$$Z_1/Z_n \approx \left(\frac{1.42}{nQ_L}\right)\left[\frac{1}{(1-1/n^2)-(0.66-2.08/n^2)/Q_L}\right]. \qquad (2)$$

in [1]-[6], when the switch duty ratio D is 50%. (b) In (2), change the factor 1.42 to 1.0147; the factor 2.08 to 1.7879; and the factor 0.66 to 0.773. (c) Recalculate the numerical

n	c_n	c_n/c_1
1	1.639	1.000
2	0.8477	0.5172
3	0.2222	0.1356
4	0.1432	0.08737
5	0.07997	0.04879
6	0.05907	0.03604
7	0.04079	0.02489
8	0.03235	0.01974
9	0.02467	0.01505
10	0.02045	0.01248

$$H2 := 20\cdot\log\left[0.5172\cdot\frac{1.0147}{2\cdot Q_L}\cdot\left[\frac{1}{\left(1-\frac{1}{2^2}\right)-\frac{\left(0.773-\frac{1.7879}{2^2}\right)}{Q_L}}\right]\right]$$

$$H3 := 20\cdot\log\left[0.1356\cdot\frac{1.0147}{3\cdot Q_L}\cdot\left[\frac{1}{\left(1-\frac{1}{3^2}\right)-\frac{\left(0.773-\frac{1.7879}{3^2}\right)}{Q_L}}\right]\right]$$

$$H4 := 20\cdot\log\left[0.08737\cdot\frac{1.0147}{4\cdot Q_L}\cdot\left[\frac{1}{\left(1-\frac{1}{4^2}\right)-\frac{\left(0.773-\frac{1.7879}{4^2}\right)}{Q_L}}\right]\right]$$

$$H5 := 20\cdot\log\left[0.04879\cdot\frac{1.0147}{5\cdot Q_L}\cdot\left[\frac{1}{\left(1-\frac{1}{5^2}\right)-\frac{\left(0.773-\frac{1.7879}{5^2}\right)}{Q_L}}\right]\right]$$

$$H6 := 20\cdot\log\left[0.03604\cdot\frac{1.0147}{6\cdot Q_L}\cdot\left[\frac{1}{\left(1-\frac{1}{6^2}\right)-\frac{\left(0.773-\frac{1.7879}{6^2}\right)}{Q_L}}\right]\right]$$

$$H7 := 20\cdot\log\left[0.02489\cdot\frac{1.0147}{7\cdot Q_L}\cdot\left[\frac{1}{\left(1-\frac{1}{7^2}\right)-\frac{\left(0.773-\frac{1.7879}{7^2}\right)}{Q_L}}\right]\right]$$

$H2 = -18.777$

$H5 = -48.497$

$H3 = -34.777$

$H6 = -52.779$

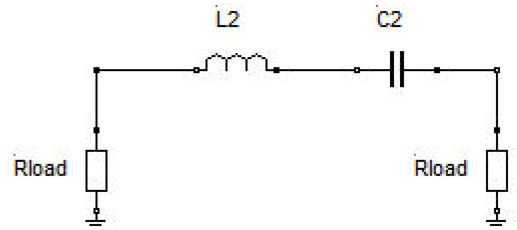
$H4 = -41.372$

$H7 = -57.374$

REFERENCE - ideal frequency response of the series tuned circuit

The series tuned circuit has a frequency response that we need to measure to compensate for the losses of this circuit in the networks below. The reason for this complexity is that the harmonics are calculated relying on a wideband constant Rload, but the extra filtering and impedance conversion on the output of the tuned circuit presents Rload only at the output frequency and not at the harmonic frequencies.

$L_2 = 50.47\,nH$ $\quad C_2 = 4.699\,pF$ $\quad R_{load} = 40.9\,ohm$ $\quad ESRL2 = 0.261\,ohm$

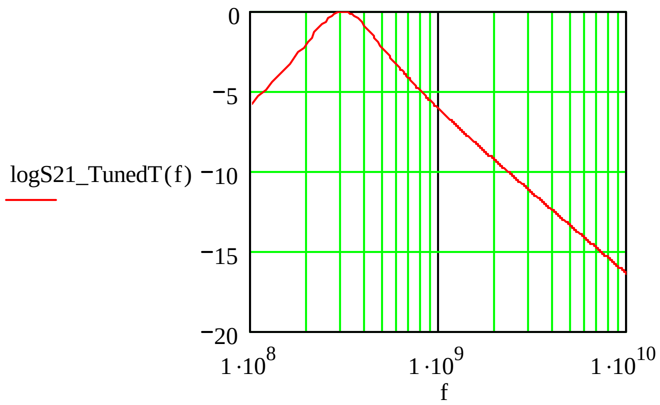


$$TunedL(freq) := \begin{bmatrix} 1 & \dfrac{j\cdot 2\cdot\pi\cdot freq\cdot\left(L_2 + L_{pcb} + L_{lopster}\right)}{ohm} + \dfrac{ESRL2}{ohm} \\ 0 & 1 \end{bmatrix}$$

$$TunedC(freq) := \begin{pmatrix} 1 & \dfrac{1}{j\cdot 2\cdot\pi\cdot freq\cdot C_2\cdot ohm} \\ 0 & 1 \end{pmatrix}$$

$$TunedT(freq) := TunedL(freq)\cdot TunedC(freq)$$

$$logS21\_TunedT(freq) := 10\log\left[\left|\frac{2\left(\dfrac{R_{load}{}^2}{ohm^2}\right)^{0.5}}{TunedT(freq)_{0,0}\cdot\dfrac{R_{load}}{ohm} + TunedT(freq)_{0,1} + \dfrac{R_{load}{}^2}{ohm^2}\cdot TunedT(freq)_{1,0} + TunedT(freq)_{1,1}\cdot\dfrac{R_{load}}{ohm}}\right|, 10\right]$$



$T1dB := logS21\_TunedT(freq)$ $\qquad T1dB = -1.415$

$T2dB := logS21\_TunedT(2\cdot freq)$ $\qquad T2dB = -5.427$

$T3dB := logS21\_TunedT(3\cdot freq)$ $\qquad T3dB = -7.405$

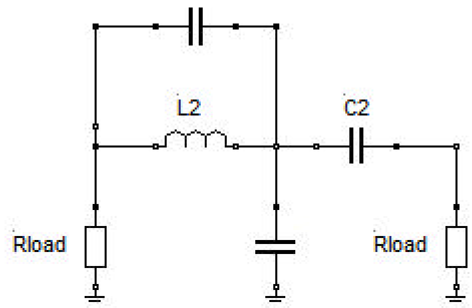
$T4dB := logS21\_TunedT(4\cdot freq)$ $\qquad T4dB = -8.731$

$T5dB := logS21\_TunedT(5\cdot freq)$ $\qquad T5dB = -9.735$

$T6dB := logS21\_TunedT(6\cdot freq)$ $\qquad T6dB = -10.547$

$T7dB := logS21\_TunedT(7\cdot freq)$ $\qquad T7dB = -11.228$

Real response of the series tuned circuit



Now calculate the frequency response of the real series tuned circuit. The effect of L1 does not need to be compensated as this is already compensated in the equationns for L1. **Cpcb2 is multiplied by 1.4.**

$$C_{L2} := \frac{1}{L_2 \cdot (2 \cdot \pi \cdot SRFL2)^2}$$

$L_2 = 50.473\,nH$ $\quad ESRL2 = 0.261\,ohm$ $\quad C_{pcb2} = 0.24\,pF$

$C_2 = 4.699\,pF$ $\quad SRFL2 = 2.97\,GHz$ $\quad C_{L2} = 0.057\,pF$

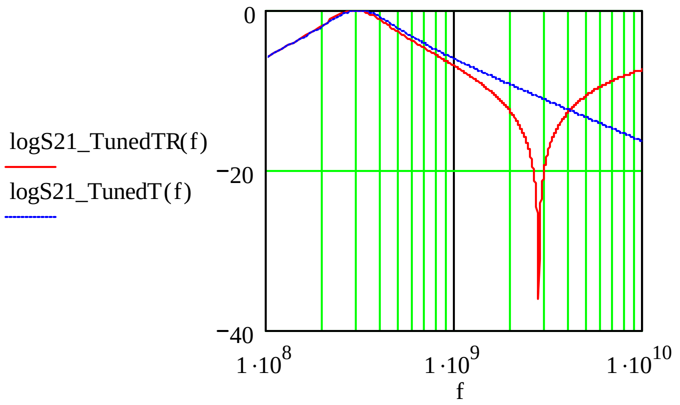
$$TA(freq) := \begin{bmatrix} 1 & \dfrac{1}{\left[\dfrac{1}{\left[\dfrac{j \cdot 2 \cdot \pi \cdot freq \cdot (L_2 + L_{pcb} + L_{lopster})}{ohm} + \dfrac{ESRL2}{ohm}\right]} + j \cdot 2 \cdot \pi \cdot freq \cdot C_{L2} \cdot ohm\right]} \\ 0 & 1 \end{bmatrix}$$

$$TB(freq) := \begin{pmatrix} 1 & 0 \\ j \cdot 2 \cdot \pi \cdot freq \cdot 1.4 \cdot C_{pcb2} \cdot ohm & 1 \end{pmatrix}$$

$$TunedTR(freq) := TA(freq)\, TB(freq)\, TunedC(freq)$$

TunedTR is the S-parameters of the real network and is used below

$$logS21\_TunedTR(freq) := 10\log\left[\left|\frac{2\left(\dfrac{R_{load}^2}{ohm^2}\right)^{0.5}}{TunedTR(freq)_{0,0} \cdot \dfrac{R_{load}}{ohm} + TunedTR(freq)_{0,1} + \dfrac{R_{load}^2}{ohm^2} \cdot TunedTR(freq)_{1,0} + TunedTR(freq)_{1,1} \cdot \dfrac{R_{load}}{ohm}}\right|, 10\right]$$



$$T1RdB := logS21\_TunedTR(freq)$$

$T1dB = -1.415$

$T1RdB = -1.792$

Now modify the harmonics with the matching network.   There four matching networks are for Rload < 50 Ohms

This section subtracts from the harmonics the extra attenuation obtained from the impedance matching network. Four networks have been designed for Rload<50R, and four networks for >50R load, giving eight in total. Half of these have a second harmonic notch. Half of these use a second LC filter stage. This calculation is done using the ABCD matrixies which are multiplied together and converted to S21 using standard equations. The frequency response of all networks are shown below, the notch helps with the second harmonic but higher harmonics get through more easiliy. The more complexity the more loss and as a simple approximation for loss, all the inductors have 1ohm in series in the equations.

1

$L_{series\_2} = 7.075\,nH$

$C_{gnd\_2} = 3.46\,pF$

$$A(freq) := \begin{pmatrix} 1 & \frac{j \cdot 2 \cdot \pi \cdot freq \cdot L_{series\_2}}{ohm} + \frac{ESRL2}{ohm} \\ 0 & 1 \end{pmatrix}$$

$$B(freq) := \begin{pmatrix} 1 & 0 \\ j \cdot 2 \cdot \pi \cdot freq \cdot C_{gnd\_2} \cdot ohm & 1 \end{pmatrix}$$

$$logS21\_1(freq) := 10 \log\left[\left| \frac{2 \left(\frac{R_{load} \cdot 50}{ohm} \right)^{0.5}}{D(freq)_{0,0} \cdot 50 + D(freq)_{0,1} + \frac{50 \cdot R_{load}}{ohm} \cdot D(freq)_{1,0} + D(freq)_{1,1} \cdot \frac{R_{load}}{ohm}} \right|, 10 \right]$$

$logS21\_1(freq) = -1.797$ $T1dB = -1.415$

$$10 \cdot \log\left(\frac{Pout\_real}{mW} \right) = 11.335$$

2

$L_{series\_2} = 7.075\,nH$

$C_{gndnew\_2} = 2.471\,pF$

$L_{new\_2} = 13.605\,nH$

$$C(freq) := \begin{pmatrix} 1 & 0 \\ \dfrac{1}{\dfrac{1}{j \cdot 2 \cdot \pi \cdot freq \cdot C_{gndnew\_2} \cdot ohm} + \dfrac{j \cdot 2 \cdot \pi \cdot freq \cdot L_{new\_2}}{ohm} + 1} & 1 \end{pmatrix}$$

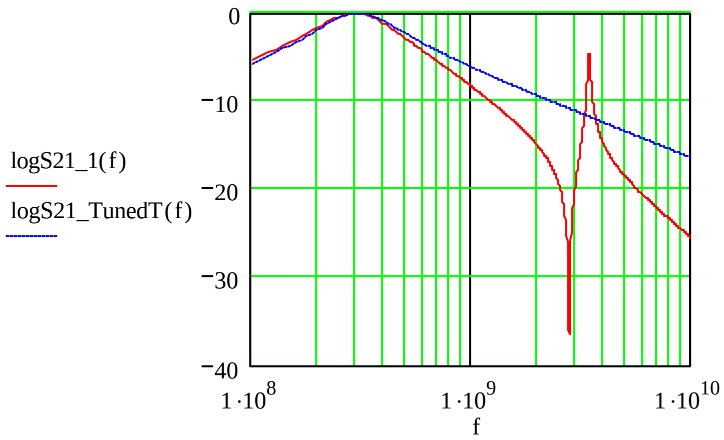
$$D(freq) := TunedTR(freq) \cdot A(freq) \cdot B(freq)$$

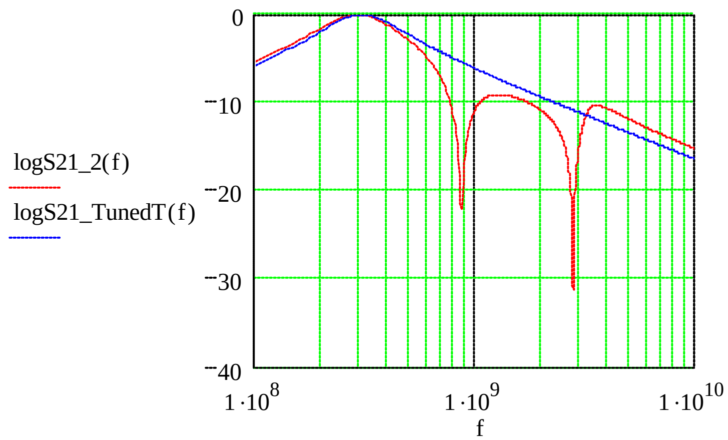
$$E(freq) := TunedTR(freq) \cdot A(freq) \cdot C(freq)$$

$$logS21\_2(freq) := 10 \log\left[\left| \frac{2 \left(\frac{R_{load} \cdot 50}{ohm} \right)^{0.5}}{E(freq)_{0,0} \cdot 50 + E(freq)_{0,1} + \frac{50 \cdot R_{load}}{ohm} \cdot E(freq)_{1,0} + E(freq)_{1,1} \cdot \frac{R_{load}}{ohm}} \right|, 10 \right]$$

$$Pout\_real\_1\_dBm := 10 \cdot \log\left(\frac{Pout\_real}{mW}\right) + logS21\_1(freq) - T1dB$$

$$Pout\_real\_2\_dBm := 10 \cdot \log\left(\frac{Pout\_real}{mW}\right) + logS21\_2(freq) - T1dB$$





Pout_real_1_dBm = 10.954

H2_1 := H2 + logS21_1(2freq) − T2dB   H2_1 = −20.518

H3_1 := H3 + logS21_1(3freq) − T3dB   H3_1 = −37.951

H4_1 := H4 + logS21_1(4freq) − T4dB   H4_1 = −46.013

H5_1 := H5 + logS21_1(5freq) − T5dB   H5_1 = −54.971

H6_1 := H6 + logS21_1(6freq) − T6dB   H6_1 = −63.376

H7_1 := H7 + logS21_1(7freq) − T7dB   H7_1 = −64.049

L1 = 180 nH   C1 = 1 pF   Icc = 10.632 mA

$C_2 = 4.699$ pF

$L_{series\_modified\_2} = 57.548$ nH $C_{gnd\_2} = 3.46$ pF

Pout_real_2_dBm = 10.948

H2_2 := H2 + logS21_2(2freq) − T2dB   H2_2 = −36.282

H3_2 := H3 + logS21_2(3freq) − T3dB   H3_2 = −36.467

H4_2 := H4 + logS21_2(4freq) − T4dB   H4_2 = −42.64

H5_2 := H5 + logS21_2(5freq) − T5dB   H5_2 = −50.447

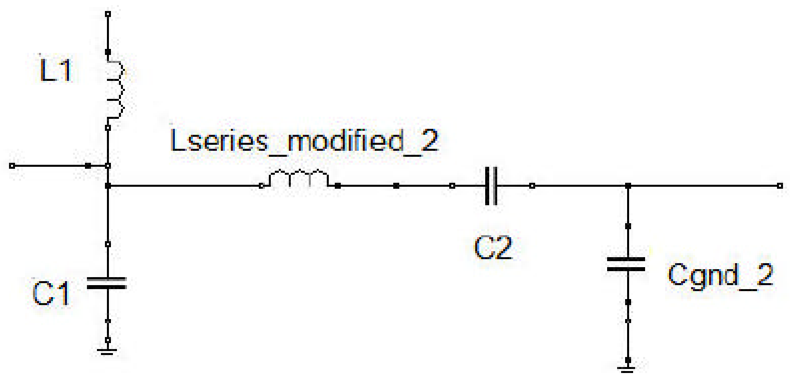
H6_2 := H6 + logS21_2(6freq) − T6dB   H6_2 = −58.105

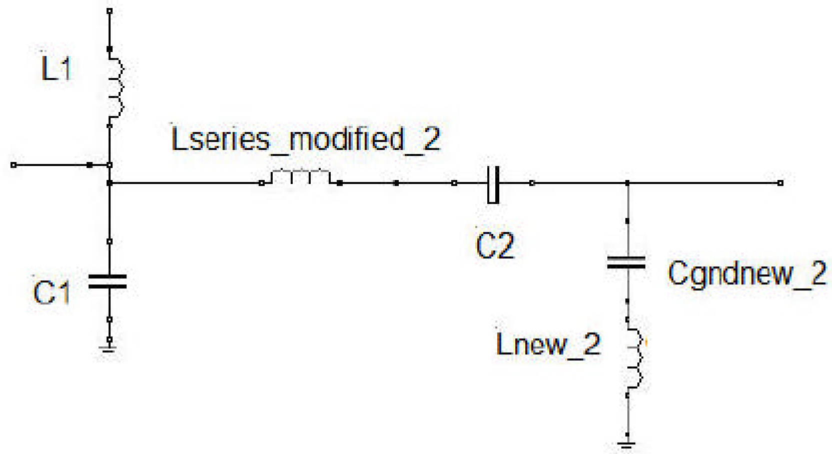
H7_2 := H7 + logS21_2(7freq) − T7dB   H7_2 = −59.636

L1 = 180 nH   C1 = 1 pF   Icc = 10.632 mA

$C_2 = 4.699$ pF $C_{gndnew\_2} = 2.471$ pF

$L_{series\_modified\_2} = 57.548$ nH $L_{new\_2} = 13.605$ nH





3

$L_{series\_2} = 7.075\,nH$ $L_{g2} = 12.232\,nH$

$C_{gnd\_2\_g1} = 22.06\,pF$ $C_{g3} = 18.601\,pF$

$$F(freq) := \begin{pmatrix} 1 & 0 \\ j\cdot 2\cdot \pi\cdot freq\cdot C_{gnd\_2\_g1}\cdot ohm & 1 \end{pmatrix}$$

$$G(freq) := \begin{pmatrix} 1 & \dfrac{j\cdot 2\cdot \pi\cdot freq\cdot L_{g2}}{ohm} + 1 \\ 0 & 1 \end{pmatrix}$$

$$H(freq) := \begin{pmatrix} 1 & 0 \\ j\cdot 2\cdot \pi\cdot freq\cdot C_{gnd\_2\_g1}\cdot ohm & 1 \end{pmatrix}$$

4

$L_{series\_2} = 7.075\,nH$ $L_{g2} = 12.232\,nH$

$C_{gndnew\_2\_g1} = 15.757\,pF$ $C_{g3} = 18.601\,pF$

$L_{new\_2\_g1} = 2.134\,nH$

$$J(freq) := \begin{pmatrix} 1 & 0 \\ \dfrac{1}{\dfrac{1}{j\cdot 2\cdot \pi\cdot freq\cdot C_{gndnew\_2\_g1}\cdot ohm} + \dfrac{j\cdot 2\cdot \pi\cdot freq\cdot L_{new\_2\_g1}}{ohm} + 1} & 1 \end{pmatrix}$$

$$I(freq) := TunedTR(freq)\cdot A(freq)\cdot F(freq)\cdot G(freq)\cdot H(freq)$$

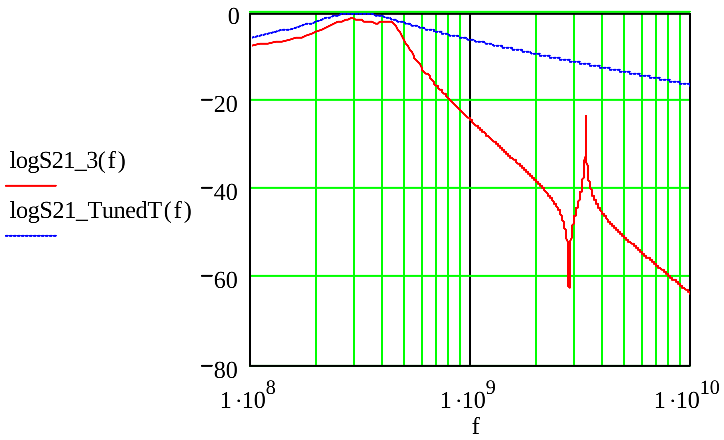
$$K(freq) := TunedTR(freq)\cdot A(freq)\cdot J(freq)\cdot G(freq)\cdot H(freq)$$

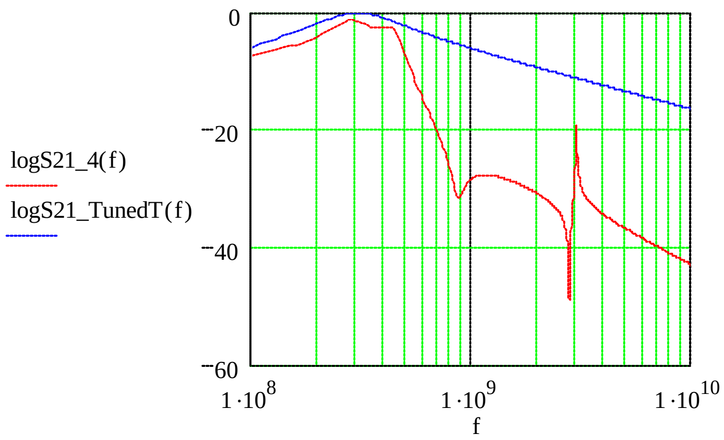
$$\text{logS21\_3}(freq) := 10\log\left[\left|\frac{2\left(\frac{R_{load}\cdot 50}{ohm}\right)^{0.5}}{I(freq)_{0,0}\cdot 50 + I(freq)_{0,1} + \frac{50\cdot R_{load}}{ohm}\cdot I(freq)_{1,0} + I(freq)_{1,1}\cdot\frac{R_{load}}{ohm}}\right|, 10\right]$$

$$\text{logS21\_4}(freq) := 10\log\left[\left|\frac{2\left(\frac{R_{load}\cdot 50}{ohm}\right)^{0.5}}{K(freq)_{0,0}\cdot 50 + K(freq)_{0,1} + \frac{50\cdot R_{load}}{ohm}\cdot K(freq)_{1,0} + K(freq)_{1,1}\cdot\frac{R_{load}}{ohm}}\right|, 10\right]$$

$$\text{Pout\_real\_3\_dBm} := 10\cdot\log\left(\frac{\text{Pout\_real}}{mW}\right) + \text{logS21\_3}(freq) - \text{T1dB}$$

$$\text{Pout\_real\_4\_dBm} := 10\cdot\log\left(\frac{\text{Pout\_real}}{mW}\right) + \text{logS21\_4}(freq) - \text{T1dB}$$





Pout_real_3_dBm = 10.824

H2_3 := H2 + logS21_3(2freq) − T2dB   H2_3 = −34.839

H3_3 := H3 + logS21_3(3freq) − T3dB   H3_3 = −57.111

H4_3 := H4 + logS21_3(4freq) − T4dB   H4_3 = −68.101

H5_3 := H5 + logS21_3(5freq) − T5dB   H5_3 = −79.128

H6_3 := H6 + logS21_3(6freq) − T6dB   H6_3 = −89.028

H7_3 := H7 + logS21_3(7freq) − T7dB   H7_3 = −90.33

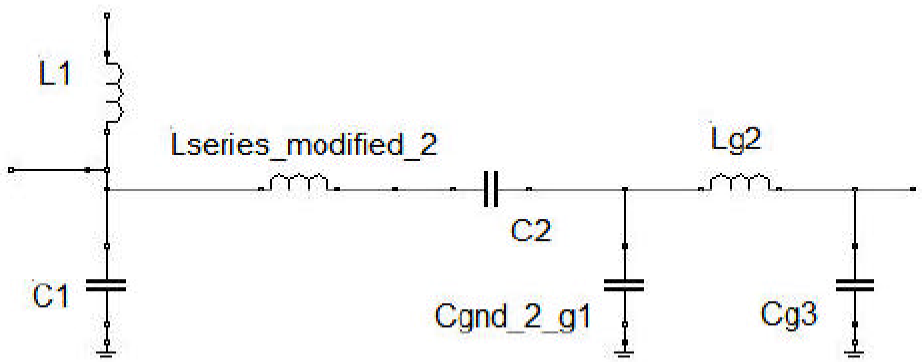
L1 = 180 nH   C1 = 1 pF   Icc = 10.632 mA

$C_2 = 4.699\,pF$

$L_{series\_modified\_2} = 57.548\,nH$

$C_{gnd\_2\_g1} = 22.06\,pF$ $L_{g2} = 12.232\,nH$

$C_{g3} = 18.601\,pF$



Pout_real_4_dBm = 10.237

H2_4 := H2 + logS21_4(2freq) − T2dB   H2_4 = −44.746

H3_4 := H3 + logS21_4(3freq) − T3dB   H3_4 = −55.272

H4_4 := H4 + logS21_4(4freq) − T4dB   H4_4 = −62.278

H5_4 := H5 + logS21_4(5freq) − T5dB   H5_4 = −70.467

H6_4 := H6 + logS21_4(6freq) − T6dB   H6_4 = −77.411

H7_4 := H7 + logS21_4(7freq) − T7dB   H7_4 = −70.624

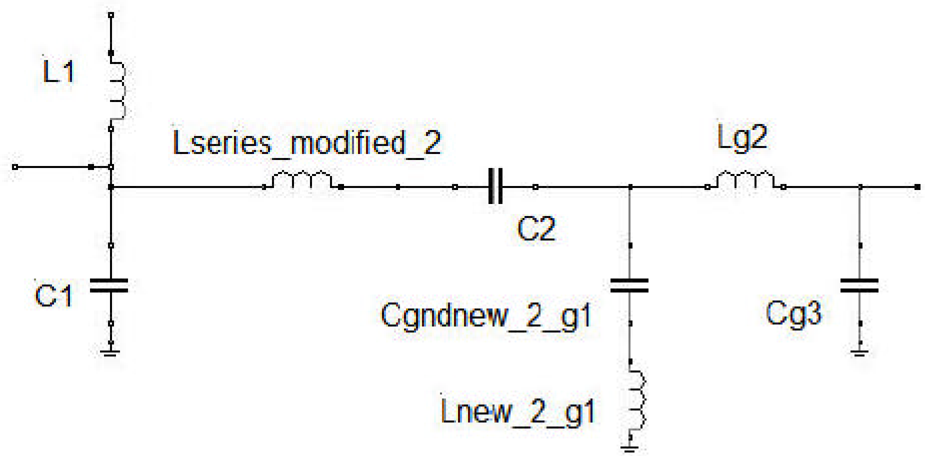
L1 = 180 nH   C1 = 1 pF   Icc = 10.632 mA

$C_2 = 4.699\,pF$

$L_{series\_modified\_2} = 57.548\,nH$

$C_{gndnew\_2\_g1} = 15.757\,pF$ $L_{g2} = 12.232\,nH$

$L_{new\_2\_g1} = 2.134\,nH$ $C_{g3} = 18.601\,pF$



These four matching networks are for Rload > 50 Ohms

5

$L_{series\_1} = 7.822i\,nH$

$C_{gnd\_1} = 3.825i\,pF$

6

$L_{series\_1} = 7.822i\,nH$

$C_{gndnew\_1} = 2.732i\,pF$

$L_{new\_1} = -12.305i\,nH$

$$L(freq) := \begin{pmatrix} 1 & 0 \\ j\cdot 2\cdot \pi\cdot freq\cdot C_{gnd\_1}\cdot ohm & 1 \end{pmatrix}$$

$$M(freq) := \begin{pmatrix} 1 & \dfrac{j\cdot 2\cdot \pi\cdot freq\cdot L_{series\_1}}{ohm} + 1 \\ 0 & 1 \end{pmatrix}$$

$$O(freq) := \begin{pmatrix} 1 & 0 \\ \dfrac{1}{\dfrac{1}{j\cdot 2\cdot \pi\cdot freq\cdot C_{gndnew\_1}\cdot ohm} + \dfrac{j\cdot 2\cdot \pi\cdot freq\cdot L_{new\_1}}{ohm} + 1} & 1 \end{pmatrix}$$

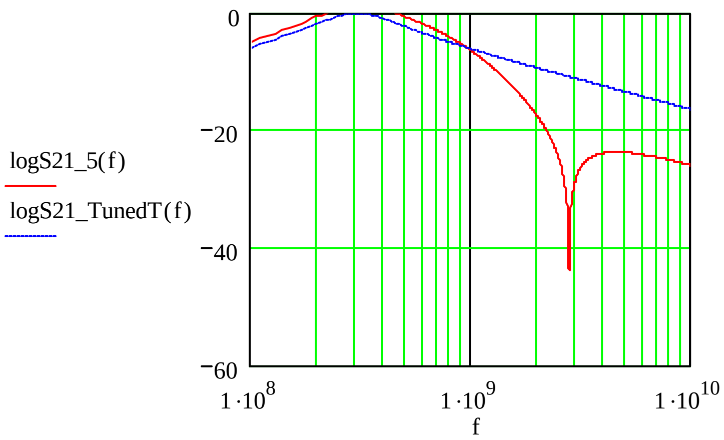
$$N(freq) := TunedTR(freq)\cdot L(freq)\cdot M(freq)$$

$$P(freq) := TunedTR(freq)\cdot O(freq)\cdot M(freq)$$

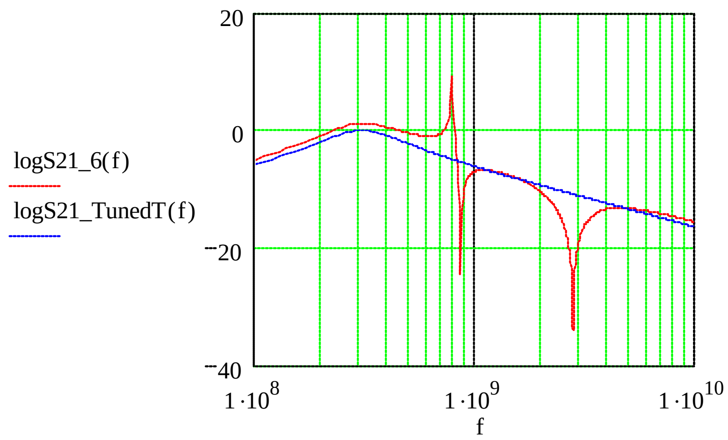
$$logS21\_5(freq) := 10\log\left[\left|\frac{2\left(\dfrac{R_{load}\cdot 50}{ohm}\right)^{0.5}}{N(freq)_{0,0}\cdot 50 + N(freq)_{0,1} + \dfrac{50\cdot R_{load}}{ohm}\cdot N(freq)_{1,0} + N(freq)_{1,1}\cdot \dfrac{R_{load}}{ohm}}\right|, 10\right]$$

$$logS21\_6(freq) := 10\log\left[\left|\frac{2\left(\dfrac{R_{load}\cdot 50}{ohm}\right)^{0.5}}{P(freq)_{0,0}\cdot 50 + P(freq)_{0,1} + \dfrac{50\cdot R_{load}}{ohm}\cdot P(freq)_{1,0} + P(freq)_{1,1}\cdot \dfrac{R_{load}}{ohm}}\right|, 10\right]$$

$$Pout\_real\_5\_dBm := 10 \cdot \log\left(\frac{Pout\_real}{mW}\right) + logS21\_5(freq) - T1dB$$



$$Pout\_real\_6\_dBm := 10 \cdot \log\left(\frac{Pout\_real}{mW}\right) + logS21\_6(freq) - T1dB$$



$Pout\_real\_5\_dBm = 12.961$

$H2\_5 := H2 + logS21\_5(3freq) - T2dB$ $\quad H2\_5 = -23.171$

$H3\_5 := H3 + logS21\_5(3freq) - T3dB$ $\quad H3\_5 = -37.192$

$H4\_5 := H4 + logS21\_5(4freq) - T4dB$ $\quad H4\_5 = -47.25$

$H5\_5 := H5 + logS21\_5(5freq) - T5dB$ $\quad H5\_5 = -58.354$

$H6\_5 := H6 + logS21\_5(6freq) - T6dB$ $\quad H6\_5 = -69.274$

$H7\_5 := H7 + logS21\_5(7freq) - T7dB$ $\quad H7\_5 = -73.691$

$L1 = 180\,nH$ $\quad C1 = 1\,pF$ $\quad Icc = 10.632\,mA$

$C_2 = 4.699\,pF$

$L_2 = 50.473\,nH$ $\quad C_{gnd\_1} = 3.825i\,pF$ $\quad L_{series\_1} = 7.822i\,nH$

$Pout\_real\_6\_dBm = 12.903$

$H2\_6 := H2 + logS21\_6(2freq) - T2dB$ $\quad H2\_6 = -28.735$

$H3\_6 := H3 + logS21\_6(3freq) - T3dB$ $\quad H3\_6 = -34.582$

$H4\_6 := H4 + logS21\_6(4freq) - T4dB$ $\quad H4\_6 = -41.631$

$H5\_6 := H5 + logS21\_6(5freq) - T5dB$ $\quad H5\_6 = -50.522$

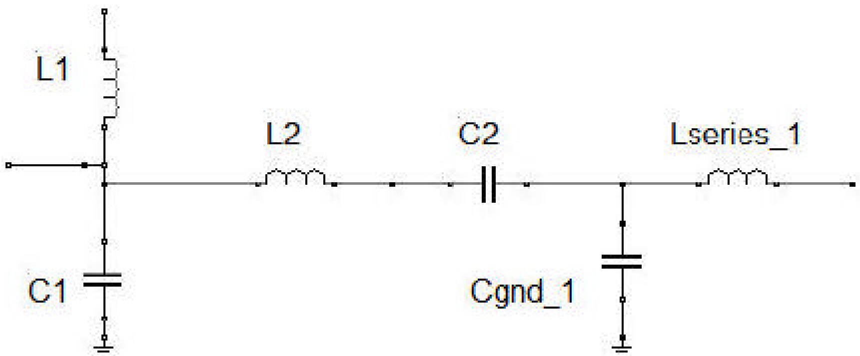
$H6\_6 := H6 + logS21\_6(6freq) - T6dB$ $\quad H6\_6 = -60.006$

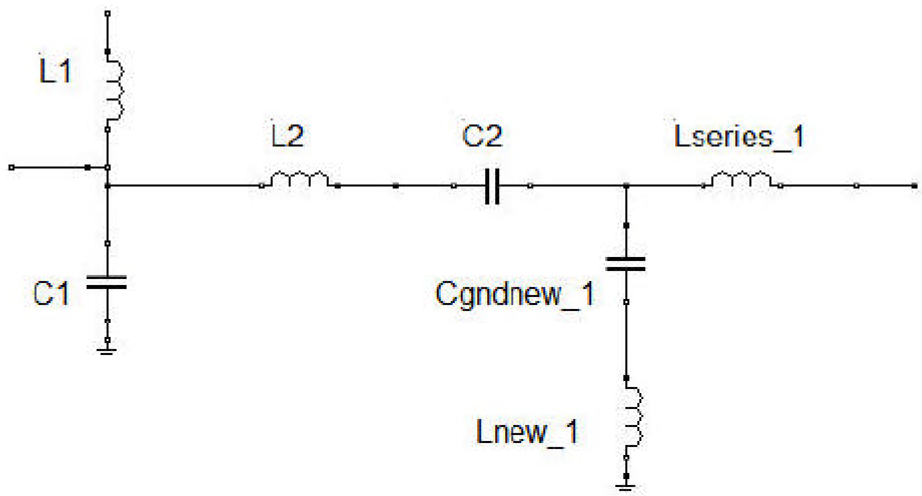
$H7\_6 := H7 + logS21\_6(7freq) - T7dB$ $\quad H7\_6 = -63.657$

$L1 = 180\,nH$ $\quad C1 = 1\,pF$ $\quad Icc = 10.632\,mA$

$C_2 = 4.699\,pF$ $\quad L_{series\_1} = 7.822i\,nH$

$L_2 = 50.473\,nH$ $\quad C_{gndnew\_1} = 2.732i\,pF$ $\quad L_{new\_1} = -12.305i\,nH$





7

$L_{series\_modified\_1} = 46.502 + 7.822i\,nH$ $L_{g3} = 46.502\,nH$

$C_{gnd\_1} = 3.825i\,pF$ $C_{g2} = 4.893\,pF$

8

$L_{series\_modified\_1} = 46.502 + 7.822i\,nH$ $L_{g3} = 46.502\,nH$

$C_{gndnew\_1} = 2.732i\,pF$ $C_{g2} = 4.893\,pF$

$L_{new\_1} = -12.305i\,nH$

$$L(freq) := \begin{pmatrix} 1 & 0 \\ j\cdot 2\cdot\pi\cdot freq\cdot C_{gnd\_1}\cdot ohm & 1 \end{pmatrix}$$

$$Q(freq) := \begin{pmatrix} 1 & \dfrac{j\cdot 2\cdot\pi\cdot freq\cdot L_{series\_modified\_1}}{ohm} + 1 \\ 0 & 1 \end{pmatrix}$$

$$R(freq) := \begin{pmatrix} 1 & 0 \\ j\cdot 2\cdot\pi\cdot freq\cdot C_{g2}\cdot ohm & 1 \end{pmatrix}$$

$$S(freq) := \begin{pmatrix} 1 & \dfrac{j\cdot 2\cdot\pi\cdot freq\cdot L_{g3}}{ohm} + 1 \\ 0 & 1 \end{pmatrix}$$

$$T(freq) := \begin{pmatrix} 1 & 0 \\ \dfrac{1}{\dfrac{1}{j\cdot 2\cdot\pi\cdot freq\cdot C_{gndnew\_1}\cdot ohm} + \dfrac{j\cdot 2\cdot\pi\cdot freq\cdot L_{new\_1}}{ohm} + 1} & 1 \end{pmatrix}$$

$$U(freq) := TunedTR(freq)\cdot L(freq)\cdot Q(freq)\cdot R(freq)\cdot S(freq)$$

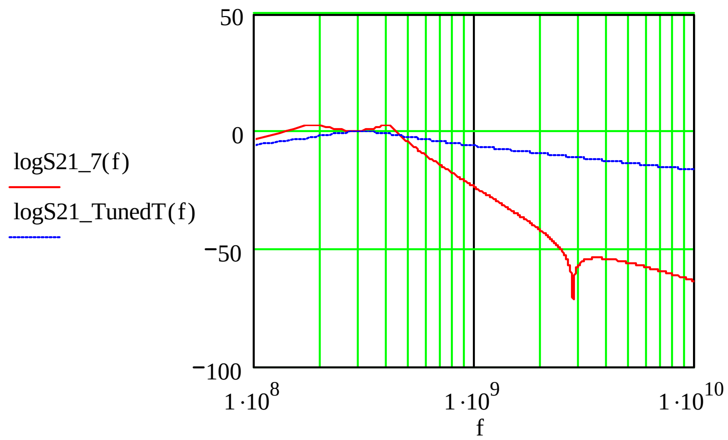
$$V(freq) := TunedTR(freq)\cdot T(freq)\cdot Q(freq)\cdot R(freq)\cdot S(freq)$$

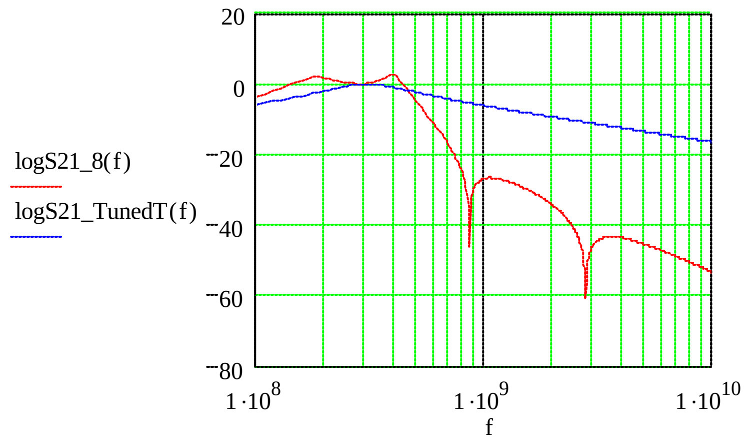
$$logS21\_7(freq) := 10\log\left[\left|\frac{2\left(\frac{R_{load}\cdot 50}{ohm}\right)^{0.5}}{U(freq)_{0,0}\cdot 50 + U(freq)_{0,1} + \frac{50\cdot R_{load}}{ohm}\cdot U(freq)_{1,0} + U(freq)_{1,1}\cdot\frac{R_{load}}{ohm}}\right|, 10\right]$$

$$logS21\_8(freq) := 10\log\left[\left|\frac{2\left(\frac{R_{load}\cdot 50}{ohm}\right)^{0.5}}{V(freq)_{0,0}\cdot 50 + V(freq)_{0,1} + \frac{50\cdot R_{load}}{ohm}\cdot V(freq)_{1,0} + V(freq)_{1,1}\cdot\frac{R_{load}}{ohm}}\right|, 10\right]$$

$$Pout\_real\_7\_dBm := 10\cdot\log\left(\frac{Pout\_real}{mW}\right) + logS21\_7(freq) - T1dB$$

$$Pout\_real\_8\_dBm := 10\cdot\log\left(\frac{Pout\_real}{mW}\right) + logS21\_8(freq) - T1dB$$





Pout_real_7_dBm = 13.341

H2_7 := H2 + logS21_7(2freq) − T2dB   H2_7 = −33.504

H3_7 := H3 + logS21_7(3freq) − T3dB   H3_7 = −57.856

H4_7 := H4 + logS21_7(4freq) − T4dB   H4_7 = −70.757

H5_7 := H5 + logS21_7(5freq) − T5dB   H5_7 = −83.784

H6_7 := H6 + logS21_7(6freq) − T6dB   H6_7 = −96.191

H7_7 := H7 + logS21_7(7freq) − T7dB   H7_7 = −101.838

L1 = 180 nH   C1 = 1 pF   Icc = 10.632 mA

$C_2 = 4.699\,pF$

$L_{series\_modified\_1} = 46.502 + 7.822i\,nH$

$L_2 = 50.473\,nH$

$C_{g2} = 4.893\,pF$ $L_{g3} = 46.502\,nH$

$C_{gnd\_1} = 3.825i\,pF$

Pout_real_8_dBm = 13.268

H2_8 := H2 + logS21_8(2freq) − T2dB   H2_8 = −50.056

H3_8 := H3 + logS21_8(3freq) − T3dB   H3_8 = −55.217

H4_8 := H4 + logS21_8(4freq) − T4dB   H4_8 = −64.318

H5_8 := H5 + logS21_8(5freq) − T5dB   H5_8 = −75.131

H6_8 := H6 + logS21_8(6freq) − T6dB   H6_8 = −86.333

H7_8 := H7 + logS21_8(7freq) − T7dB   H7_8 = −91.443

L1 = 180 nH   C1 = 1 pF   Icc = 10.632 mA

$C_2 = 4.699\,pF$

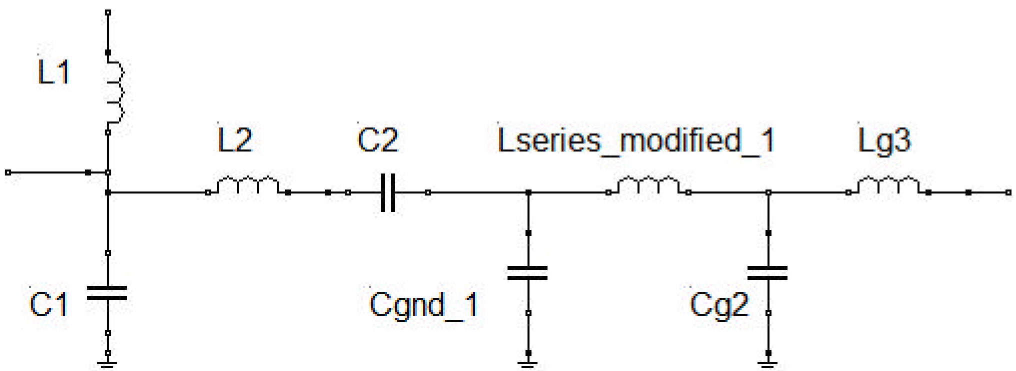
$L_2 = 50.473\,nH$

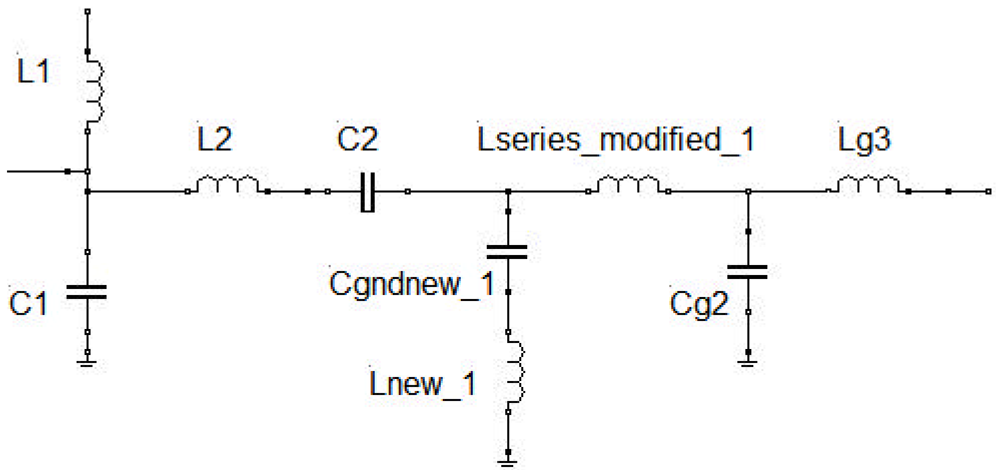
$C_{gndnew\_1} = 2.732i\,pF$

$L_{series\_modified\_1} = 46.502 + 7.822i\,nH$

$C_{g2} = 4.893\,pF$ $L_{g3} = 46.502\,nH$

$L_{new\_1} = -12.305i\,nH$





LPF Frequency Response and for Chebychev Polynomials

This subroutine is to calculate the Tchebychev polynomials for a third oder filter that can be used after the tuned network to futher attenuate the harmonincs. This filter is only used if R<50, as it requires three components with the first is merged with the final stage output capacitor. When R>50, we only have two stages and so the butterworth coefficients are used 1.414, 1.414.

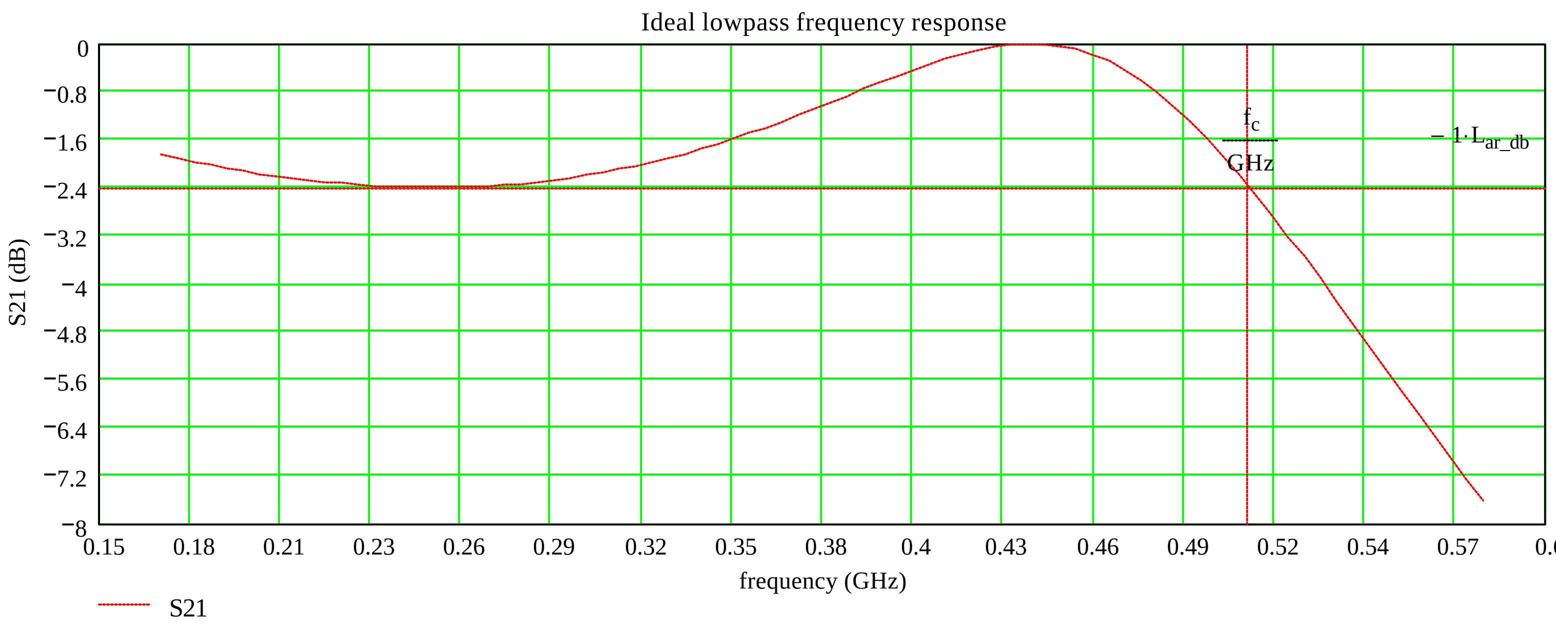
$N := 3$ order of the filter

$f_c := freq \cdot FR$

$f_{lp\_hp\_sweep\_narrow} := \frac{f_c}{3}, \frac{f_c}{3} + \frac{f_c}{100} .. f_c \cdot 1.15$

$\varepsilon := 10^{\frac{L_{ar\_db}}{10}} - 1$

$$L_A(f, f_1) := \begin{cases} 10 \cdot \log\left[1 + \varepsilon \cdot \left[\cos\left(\left(N \cdot \text{acos}\left(\frac{f}{f_1}\right)\right)\right)\right]^2\right] & \text{if } f \le f_1 \\ 10 \cdot \log\left[\left[1 + \varepsilon \cdot \left[\cosh\left(\left(N \cdot \text{acosh}\left(\frac{f}{f_1}\right)\right)\right)\right]^2\right]\right] & \text{if } f > f_1 \end{cases}$$



Calculate the g Polynomials

$k := 1..N$ $\quad \beta := \ln\left(\coth\left(\frac{L_{ar\_db}}{17.37}\right)\right)$ $\quad \gamma := \sinh\left(\frac{\beta}{2 \cdot N}\right)$ $\quad a_k := \sin\left[\frac{(2 \cdot k - 1) \cdot \pi}{2 \cdot N}\right]$ $\quad b_k := \gamma^2 + \left(\sin\left(\frac{k \cdot \pi}{N}\right)\right)^2$ $\quad g_k := 0$ $\quad g_0 := 1$ $\quad g_{N+1} := 1$

$$g_k := \begin{cases} \frac{2 \cdot a_1}{\gamma} & \text{if } k = 1 \\ \frac{4 \cdot a_{k-1} \cdot a_k}{b_{k-1} \cdot g_{k-1}} & \text{otherwise} \end{cases}$$

$g_1 = 2.967$ $\quad g_2 = 0.78$ $\quad g_3 = 2.967$

g(0) and g(N+1) represent th
input/output coupling
for odd order filters, these are 1
representing the generator (and
equal) load resistance