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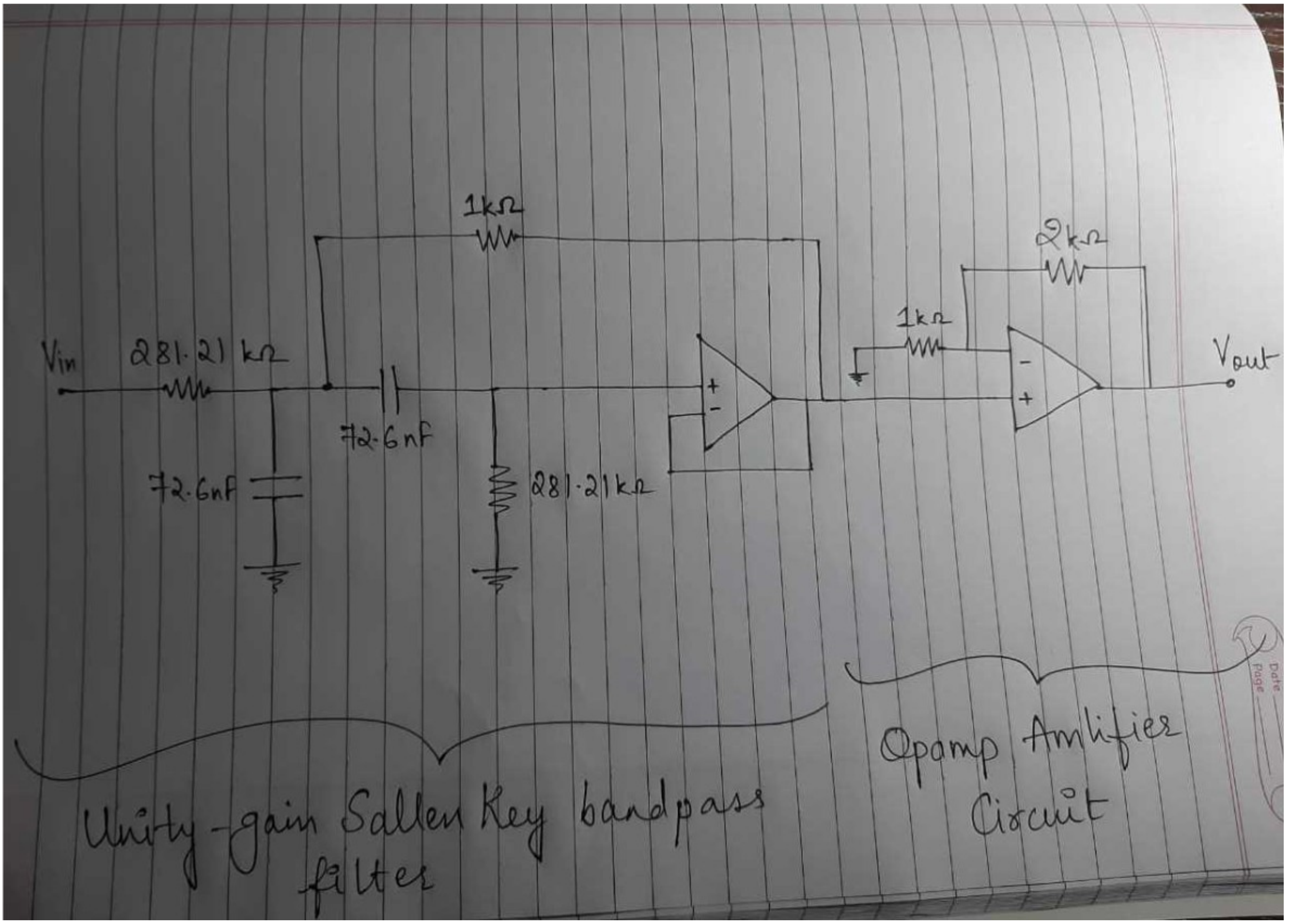
BE-PROJECT:
NARROW BAND AUDIO FILTER CIRCUIT

After studying, a few types of 2nd order bandpass filters, I concluded that Sallen-Key works the best as it's giving the best narrow-band response according to my frequency values.

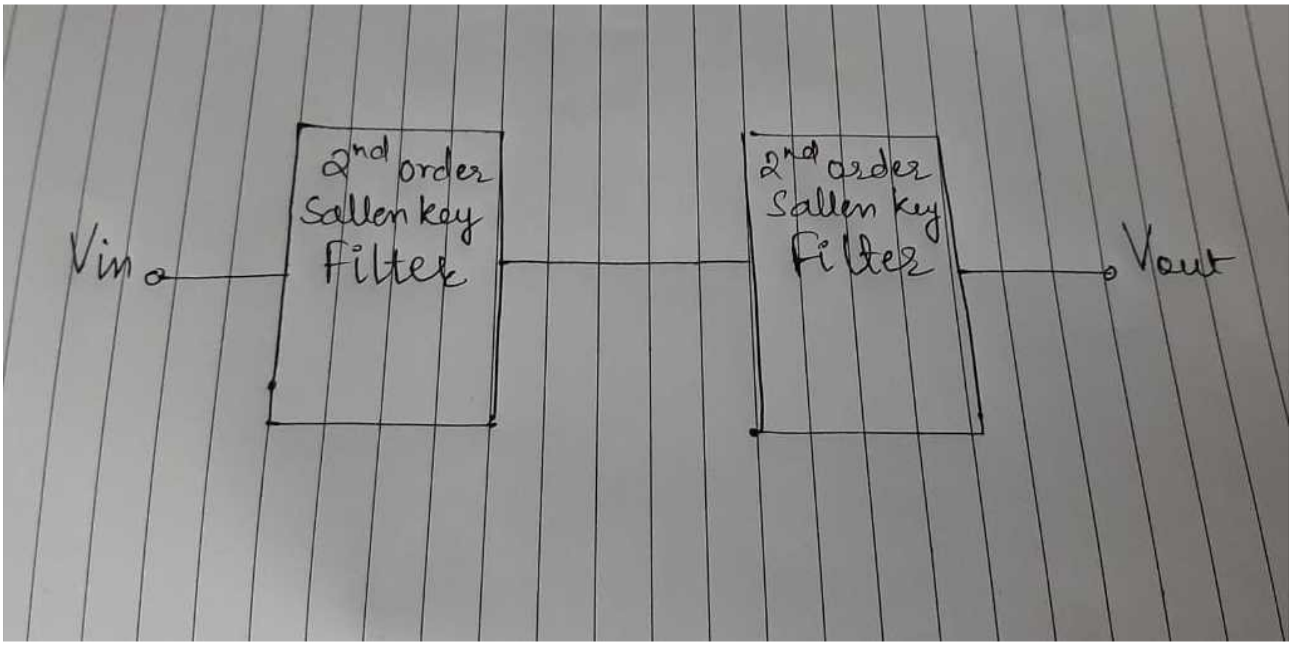
I have used a **unity-gain Sallen Key topology** to create the required narrow-bandpass filter circuit. After this, in the Bode plot of this filter, at peak I didn't have Vout/Vin=1V. Thus, to solve this, I have used an **opamp amplifier** (non-inverting) circuit to amplify the final output voltage (because Vout/Vin at peak was less than 1V) so as to get Vout/Vin=1V at the peak.

Below is the filter circuit with the component values.

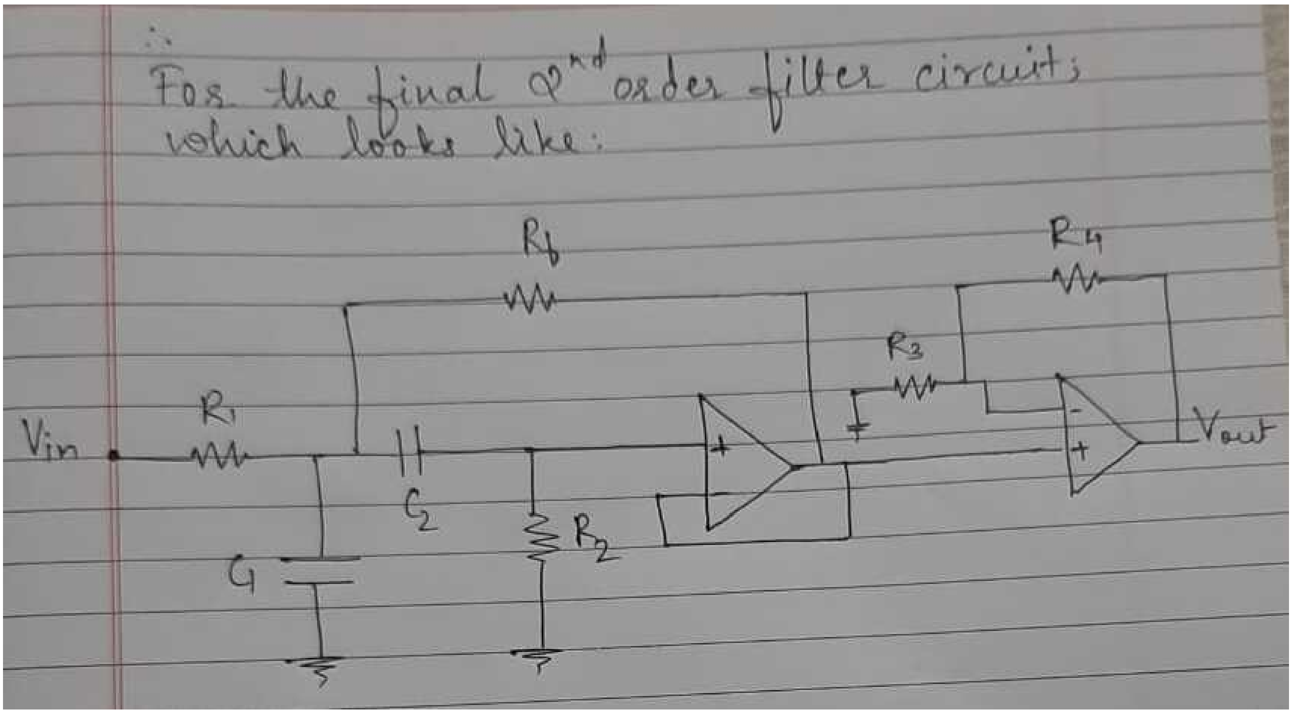


I plotted the Bode plot for the above circuit, I got the peak at f4 (as required) and amplitude of the output at f5 was less than 0.75V (as required) but the ratio of amplitudes at frequencies f3 and f4 (i.e. v3/v4) was still greater than 0.75.
Thus to reduce it, I have cascaded the above 2nd order filter circuit with the same circuit again to get a final 4th order filter circuit to meet all the specifications (v3 < 0.75V , v5 < 0.75V and peak of 1V at f4).

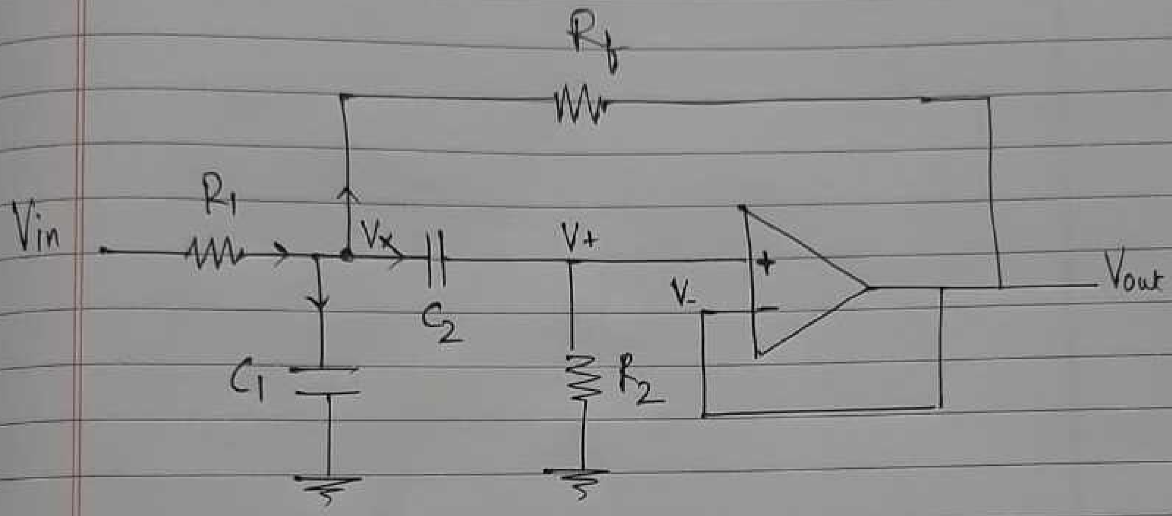
The block diagram of the final cascaded 4th order filter circuit:



Transfer-Function Detailed Derivation:



Transfer function for a unity-gain Sallen Key Bandpass Filter.



This is an ideal opamp

$\therefore$

$$V_+ = V_- = V_{out} \quad \text{—— (1)}$$

Writing KCL at V_x node:

$$\boxed{\frac{V_{in} - V_x}{R_1} = \frac{V_x}{Z_{C_1}} + \frac{V_x - V_{out}}{R_f} + \frac{V_{out}}{R_2}} \quad \text{—— (2)}$$

Here $Z_{C_1} = \dfrac{1}{jwC_1} = \dfrac{1}{sC_1}$

$[\because s = jw]$

Applying KCL at V_+ nodes

$$\frac{V_x - V_+}{Z_{C_2}} = \frac{V_+}{R_2}$$

[By eqn 1 ; $V_+ = V_{out}$]

$\therefore$

$$\frac{V_x - V_{out}}{Z_{C_2}} = \frac{V_{out}}{R_2}$$

$$\therefore \; V_x = V_{out}\left(1 + \frac{Z_{C_2}}{R_2}\right)$$

$$\left[\text{And } Z_{C_2} = \frac{1}{jWC_2} = \frac{1}{SC_2}\right]$$

$$\therefore \boxed{V_x = V_{out}\left(1 + \frac{1}{SC_2R_2}\right)} \quad \text{— } 3$$

Putting eqn 3 in eqn 2 ;

$$\frac{V_{in}}{R_1} = V_x\left(\frac{1}{R_1} + sC_1 + \frac{1}{R_f}\right) + V_{out}\left(\frac{1}{R_2} - \frac{1}{R_f}\right)$$

$$\frac{V_{in}}{R_1} = V_{out}\left(\frac{1}{R_1} + sC_1 + \frac{1}{R_f} + \frac{R_1+R_f}{SC_2R_2R_1R_f} + \frac{SC_1}{SC_2R_2}\right) + V_{out}\left(\frac{1}{R_2} - \frac{1}{R_f}\right)$$

$$\frac{V_{in}}{R_1} = V_{out}\left(\frac{1}{R_1} + \frac{1}{R_2} + sC_1 + \frac{C_1}{C_2 R_2} + \frac{R_1 + R_f}{sC_2 R_1 R_2 R_f}\right)$$

Divide by C_1;

$$\frac{V_{in}}{C_1 R_1} = V_{out}\left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + s + \frac{1}{C_2 R_2} + \frac{R_1 + R_f}{sC_1 C_2 R_1 R_2 R_f}\right)$$

Multiply by s;

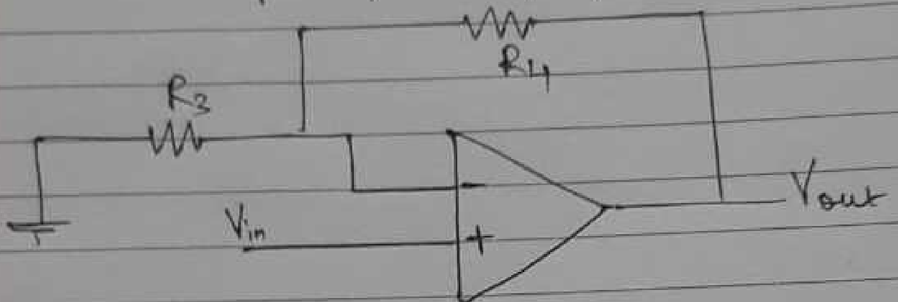
$$\frac{s.V_{in}}{C_1 R_1} = V_{out}\left(s^2 + \left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_2 R_2}\right)s + \frac{R_1 + R_f}{C_1 C_2 R_1 R_2 R_f}\right)$$

$$\boxed{\therefore \frac{V_{out}}{V_{in}} = \frac{s/C_1 R_1}{s^2 + \left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_2 R_2}\right)s + \frac{R_1 + R_f}{C_1 C_2 R_1 R_2 R_f}}}$$

This is the transfer function for the unity-gain Sallen Key we need in the filter circuit.

Now,
we have also need an opamp amplifier circuit to make the peak ~~as~~ 1V at f_4 frequency, as by only using the previous Sallen key, the peak value was coming less than 1V.

∴ The opamp amplifier circuit:



$$V_{out} = V_{in}\left(1 + \frac{R_4}{R_3}\right)$$

Therefore, the final Transfer-function of the filter used, is:

$$\frac{V_{out}}{V_{in}} = \frac{\left(1 + \frac{R_4}{R_3}\right)\frac{s}{C_1 R_1}}{s^2 + \left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_2 R_2}\right)s + \frac{R_1 + R_f}{C_1 C_2 R_1 R_2 R_f}}$$

[where $s = j\omega$]

<u>Designing the filter:</u>

The transfer function looks like:

For the unity gain Sallen key:

$$\frac{V_{out}}{V_{in}} = \frac{s/C_1 R_1}{s^2 + \left(\frac{1}{C_1 R_1} + \frac{1}{C_1 R_2} + \frac{1}{C_2 R_2}\right)s + \frac{R_1 + R_f}{C_1 C_2 R_1 R_2 R_f}}$$

$\therefore$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{R_1 + R_f}{C_1 C_2 R_1 R_2 R_f}} \quad \text{— (1)}$$

Central frequency

and

$$Q = \frac{\sqrt{(R_1 + R_f) R_1 R_2 R_f C_1 C_2}}{R_1 R_f (C_1 + C_2) + R_2 C_2 R_f} \quad \text{— (2)}$$

Quality factor

I have; f_4 (peak) = 130.81 Hz

$BW = f_5 - f_3$

$= 146.81 - 123.47$

$= 23.36$ Hz

$$Q = \frac{f_H}{BW} = \frac{130.81}{23.36} = \underline{\underline{5.6}}$$

<u>Doing the calculations:</u>

Taking:

$$C_1 = C_2 = C$$
$$R_1 = R_2 = R$$
$$R_f = 1k\Omega$$

$\therefore$ <u>In eqn (1);</u>

$$130.81 = \frac{1}{2\pi}\sqrt{\frac{1000+R}{C^2 \cdot R^2 \cdot 1000}} \quad \text{—— (3)}$$

<u>In eqn (2);</u>

$$5.6 = \frac{\sqrt{(R+1000)R^2C^2 \cdot 1000}}{R(1000)(2C) + R(1000)C}$$

$$5.6 = \frac{\cancel{CR}\sqrt{(1000)(R+1000)}}{3\cancel{RC}(1000)}$$

$$16800 = \sqrt{(1000)(R+1000)}$$

$$282210\cancel{000} = 10\cancel{00}(R+1000)$$

$\therefore$

$$R = 281210\ \Omega$$

$\therefore$

$$\boxed{R = 281.21\ k\Omega}$$

$\therefore$ In eqn (1):

$$C = \frac{1}{2\pi(130.81)}\sqrt{\frac{1000+R}{R^2 \cdot 1000}}$$

$$= \underline{\underline{72.6\ nF}}$$

$\therefore$

Component values:

$\boxed{R_1 = R_2 = 281.21\ k\Omega}$

$\boxed{C_1 = C_2 = 72.6\ nF}$ $\boxed{R_f = 1\ k\Omega}$

Now; for the opamp amlifier circuit:

We got a peak at 333mV when we plotted the Bode plot of only the unity-gain Sallen key.

Thus, we need to amplify this to 1V to have a peak of 1V.

$$\therefore \quad V_{out} = \left(1 + \frac{R_4}{R_3}\right) V_{in}$$

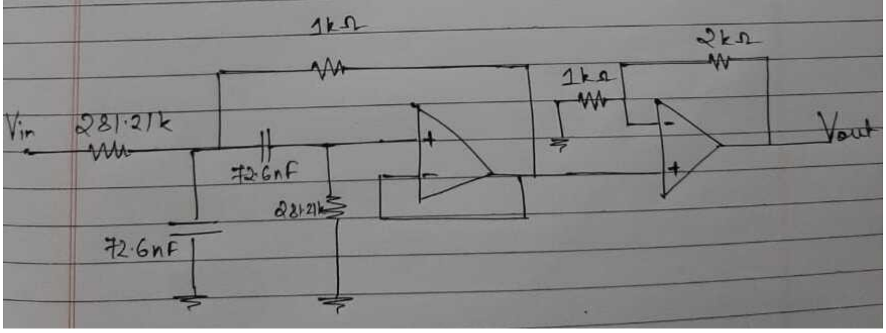
$$1 = \left(1 + \frac{R_4}{R_3}\right) \frac{333}{1000}$$

$$\therefore \quad \frac{R_4}{R_3} = 2$$

$\therefore$ Taking $\boxed{R_3 = 1\,k\Omega}$

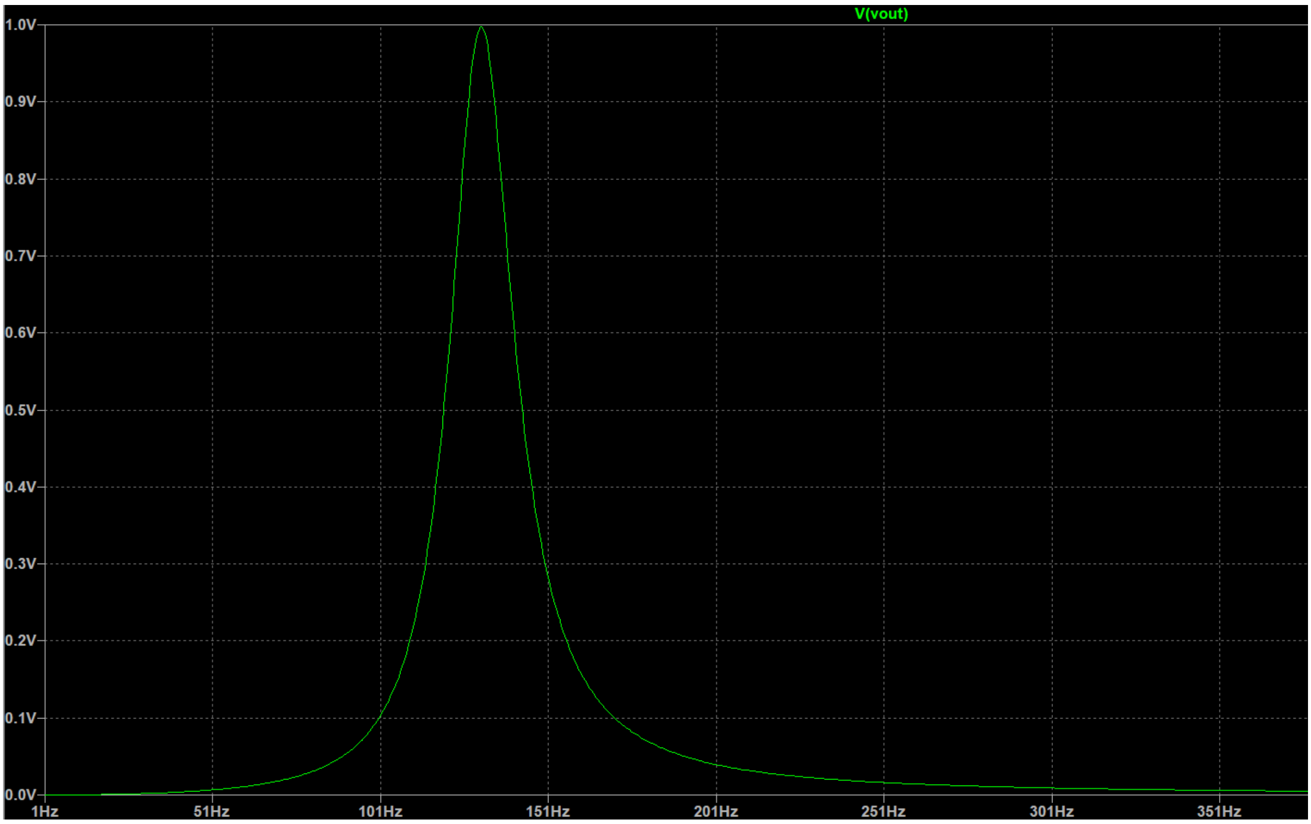
$\therefore \quad \boxed{R_4 = 2\,k\Omega}$

$\therefore$ The final 2^{nd} order filter circuit:



My Graphs:

The Bode Plot of the Designed Filter circuit:



The final filtered response looks like: