# Circuit Theory and Electronics Fundamentals

Integrated Master's in Aerospace Engineering, Técnico, University of Lisbon

Laboratory 5 Report

Francisco Alves 95787, Tomás Nunes 95855, Rodrigo Sequeira 96480

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## Contents



## 1 Introduction

In this laboratory assignment, we are asked to create a Band Pass Filter (BPF), in which we are supposed to design its architecture using one 741 OPAMP, resistors and capacitors. The goal is to achieve the best ratio between the cost of the circuit and its quality in terms of the specifications asked (Merit Figure): a central frequency $f_c = 1kHz$ and a central gain of $40dB$.

To build the circuit, we used 4 resistors, 2 capacitors and a 741 OPAMP. A representative image of the circuit can be seen in 1.

In Section 2, a theoretical analysis of the circuit using Octave is presented. In Section 3, the circuit is analysed by simulation with Ngspice software and the results are compared to the theoretical results in Section 5. Some comments about the in-person simulation are stated in Section 4. Conclusions of this study can be found in Section 6.

The components used have the following values:

Table 1: Values in SI units.

| | |
|---|---|
| $R_1$ | $1000$ |
| $R_2$ | $1000$ |
| $R_3$ | $315000$ |
| $R_4$ | $1000$ |
| $C_1$ | $220 \times 10^{-9}$ |
| $C_2$ | $220 \times 10^{-9}$ |

Note that $R_3$ is the equivalent resistance of 3 $100000\Omega$ resistors in series, that are also in series with a $10000\Omega$ resistor, and this group of resistors is in series with a parallel of 2 resistors (both with $10000\Omega$). It goes as follows: 100000 + 100000 + 100000 + 10000 + (10000//10000).

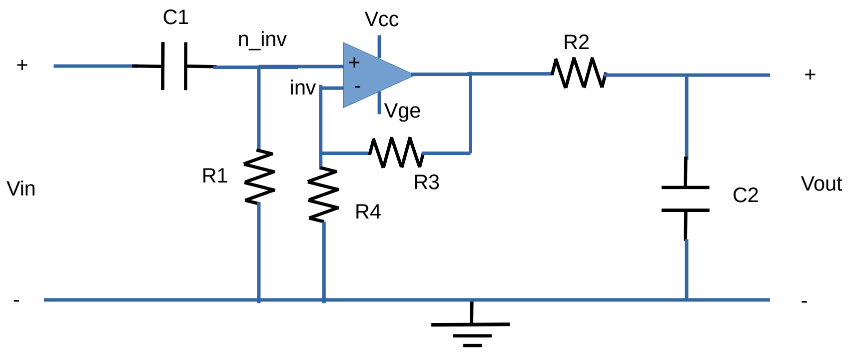


Figure 1: Circuit in study.

## 2 Theoretical Analysis

In this section, the circuit shown in Figure 1 is analysed theoretically.

The Transfer Function is given by the following equation,

$$T = \frac{R_1 C_1 s}{1 + R_1 C_1 s}\left(1 + \frac{R_3}{R_4}\right)\frac{1}{1 + R_2 C_2 s} \tag{1}$$

where $s = 2\pi f \times j$.

The frequency of the low pass filter part of the circuit is computed as

$$\omega_L = \frac{1}{R_2 C_2} \tag{2}$$

and the frequency of the high pass filter part of the circuit is given by

$$\omega_H = \frac{1}{R_1 C_1} \tag{3}$$

This leads to a central frequency expressed as

$$\omega_C = \sqrt{\omega_L \times \omega_H} \tag{4}$$

Dividing the value obtained from equation 4 by $2\pi$, we get one of the values of interest of the circuit, which should be of $1kHz$.

| Name | Value [Hz] |
|---|---|
| $f_L$ | 723.43 |
| $f_H$ | 1446.86 |
| $f_O$ | 1023.09 |

Table 2: Frequencies

The gain of the circuit is given by the formula below,

$$Gain = |\frac{R_1 C_1 \omega_C j}{1 + R_1 C_1 \omega_C j} \times (1 + \frac{R_3}{R_4}) \times \frac{1}{1 + R_2 C_2 \omega_C j}| \tag{5}$$

Also, the input impedance is given by

$$Z_{in} = |R_1 + \frac{1}{j\omega_C C_1}| \tag{6}$$

and the output impedance as

$$Z_{out} = |\frac{1}{j\omega_C C_2 + \frac{1}{R_2}}| \tag{7}$$

| Name | Value [dB] |
|---|---|
| $gain$ | 105.31 |
| $gain_{dB}$ | 40.449 |
| $Z_{IN}$ | 1758.81 |
| $Z_{OUT}$ | 586.13 |

Table 3: Gain and impedances

Here we present the plots of the output voltage gain and phase functions.

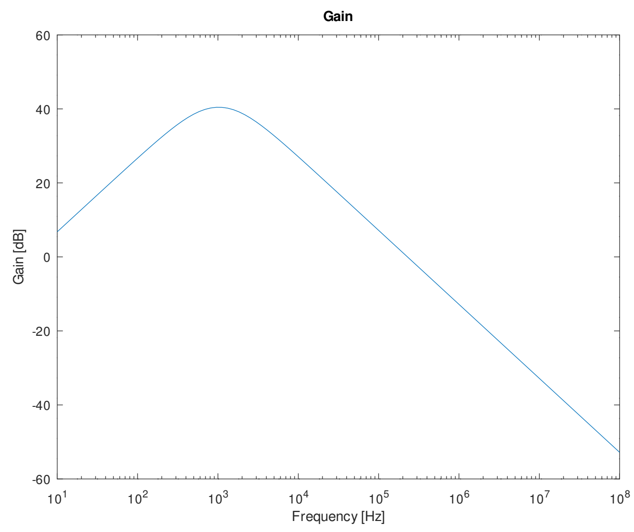


Figure 2: Output voltage gain in order to frequency

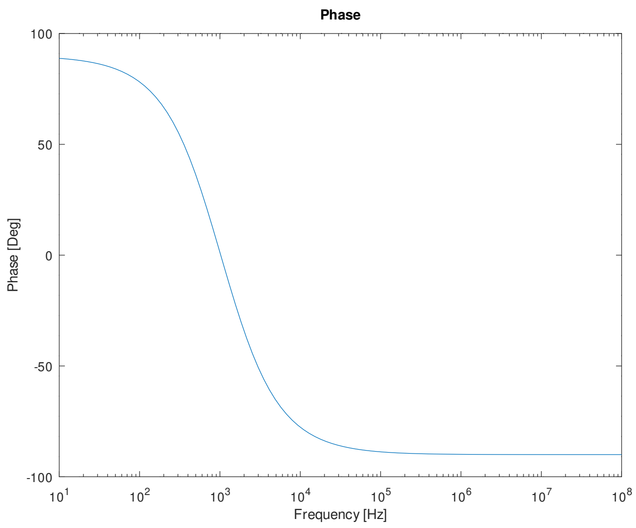


Figure 3: Phase in order to frequency

Here we present the merit figure of our circuit.

| Name | Value [Hz] [Mu] |
|---|---|
| $gain_{dev}$ | 5.308950 |
| $freq_{dev}$ | 23.0867 |
| $Cost$ | 13656.66 |
| $Merit$ | 2.578715e-06 |

Table 4: Merit figure

# 3 Simulation Analysis

## 3.1 Frequency Analysis

The frequency analysis was done in order to obtain the gain of the circuit as a function of the frequency.

The following plot shows the function we obtained for $V_{out}$, in dB, and it is also presented a plot of the phase function.

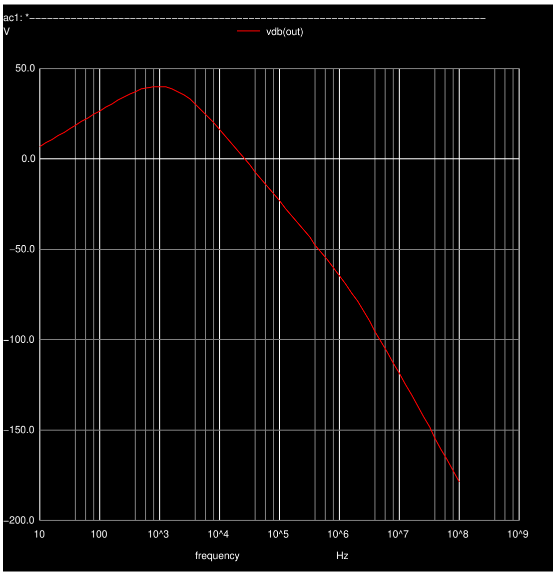


Figure 4: vOUT (dB)

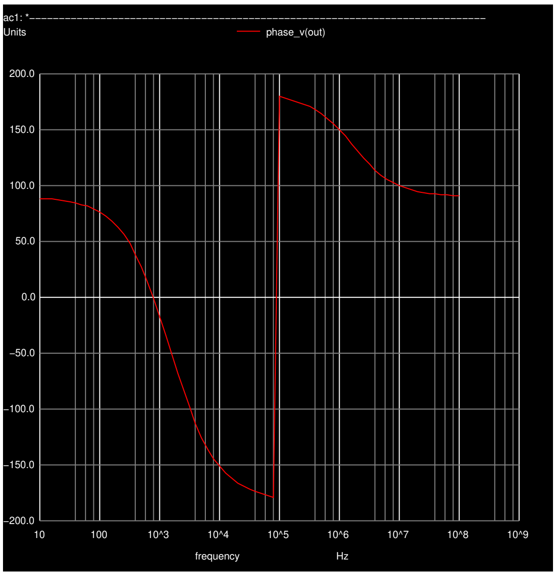


Figure 5: phase (degrees)

From this analysis, we can also obtain the values for the output voltage gain in the passband, the central frequency, and the input and output impedances at this stage.

| **Name** | **Value [dB]** |
|---|---|
| gain | 1.005979e+02 |
| gaindb | 4.005178e+01 |
| zin | 1.759004e+03 |
| zout | 5.911203e+02 |

Table 5: Gain, output and input impedance

We can also obtain the values for the upper, lower cut off and central frequencies.

| Name | Value [Hz] |
|---|---|
| fl | 3.867110e+02 |
| fh | 2.058741e+03 |
| fo | 1.000000e+03 |

Table 6: Frequencies

### 3.2 Merit Figure

In this section, we present the costs of the components and the total cost of the circuit, as well as the merit figure.

| Name | Value [Hz] [Mu] |
|---|---|
| gaindev | 5.979197e-01 |
| freqdev | 0.000000e+00 |
| cost | 1.365666e+04 |
| merit | 1.224650e-04 |

Table 7: Merit figure

## 4 In-person simulation

Due to the lack of time during the laboratory class, we couldn't build the entire circuit. However, we were able to make some measurements of interest.

The $V_{cc}$ tension read in the multimeter was of value $10.097V$ and the $V_{cc}^{-}$ tension was of magnitude $-10.030V$.

The input amplitude of the signal was read and measured with the oscilloscope which registered $0.221V$ and the output amplitude registered $2.450V$. This translates in a gain of about $11.086V$, which is close to the pretended gain.

Due to the pandemic, we couldn't attend laboratory classes during the semester, so this last laboratory assignment showed us that it is not easy to build circuits and that values can vary with lots of outside factors. The programming skills aquired are surely useful, but some hands-on experience in the future will be a good improvement in our skill set.

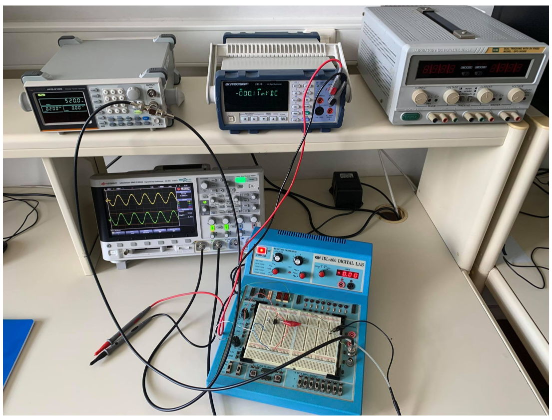

Figure 6: instruments

# 5 Side-by-side

As a viewer's reference note, the theoretical values are presented on the left and the simulation values on the right.

| Name | Value [Hz] | Name | Value [Hz] |
|---|---|---|---|
| $f_L$ | 723.43 | fl | 3.867110e+02 |
| $f_H$ | 1446.86 | fh | 2.058741e+03 |
| $f_O$ | 1023.09 | fo | 1.000000e+03 |

Table 8: Comparison 1

As seen, all values are of the same magnitude, so the differences are minimal but they exist due to the assumption of ideal model of the OPAMP. Note that in the Ngspice simulation the central frequency has the exact magnitude asked.

| Name | Value [dB] | Name | Value [dB] |
|---|---|---|---|
| $gain$ | 105.31 | gain | 1.005979e+02 |
| $gain_{dB}$ | 40.449 | gaindb | 4.005178e+01 |
| $Z_{IN}$ | 1758.81 | zin | 1.759004e+03 |
| $Z_{OUT}$ | 586.13 | zout | 5.911203e+02 |

Table 9: Comparison 2

The gains and impedances are also identical as observed in the table above. Once again the simulation value is very close to the value required. However, the output impedance is relatively high.

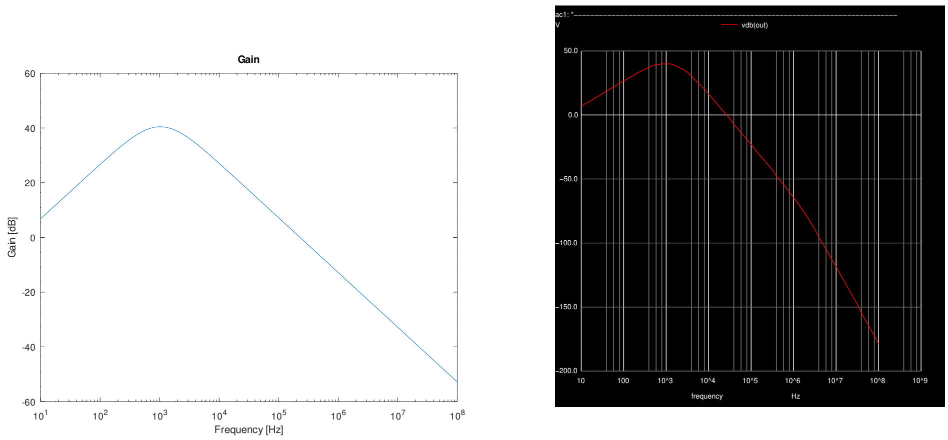


Figure 7: Output voltage gain in order to frequency

The theoretical and simulated output voltage gain functions also behave identically, as observed in the plots.

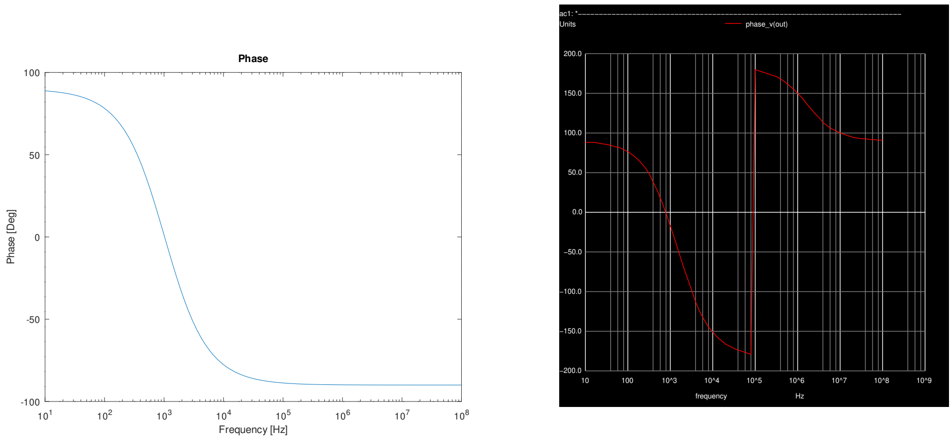


Figure 8: Phase in order to frequency

The phase plots in order to frequency may seem different at first, but they show the same behavior: the amplitudes are 180 degrees on both plots, but the origin of the plots are in different spots.

| Name | Value [Hz][Mu] | Name | Value [Hz][Mu] |
|---|---|---|---|
| $gain_{dev}$ | 5.308950 | gaindev | 5.979197e-01 |
| $freq_{dev}$ | 23.0867 | freqdev | 0.000000e+00 |
| $Cost$ | 13656.66 | cost | 1.365666e+04 |
| $Merit$ | 2.578715e-06 | merit | 1.224650e-04 |

Table 10: Comparison 4

Here, apart from the frequency deviation and merit, all values are of the same magnitude. The simulation's merit is higher because of the frequency deviation, which is null in Ngspice's results, whereas in Octave it isn't.

## 6 Conclusion

All in all, this laboratory assignment showed that the difference between the theoretical models and the simulation is minimal, never differing significantly as seen in Section 5.

This lab assignment showed us how to design a BPF circuit, which are widely used in wireless transmitters and receivers, being a key component in many contemporary applications. Once again, the in-person lab class gave us a hint of how the pratical approach differs from programmed simulations.

We consider that the merit achieved is frankly good (partly because of the exact values of the central frequency and gain), which means our circuit would be a good solution in terms of quality-cost relation for a company. In the end of the day, that will be one of multiple challenges in an engineer's life.