T5 - Band Pass Filter using OPAMP

Integrated Master in Physics Engineering

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Contents

1 Introduction

In this laboratory assignment we seek to build a bandpass filter using an OP-AMP. Particularly we seek to maximize our **merit figure**, M, given by:

$$M = \frac{1}{Cost(VoltageGainDeviation + CentralFreqDeviation + 10^{-6})}$$

where the voltage gain deviation is the absolute value of the difference between the gain at 1000 Hz and 40 dB; and the central frequency deviation is the absolute value of the difference between the central frequency and 1000 Hz. The central frequency, f_c , is given by the geometric mean of the low cut-off frequency and the high cut-off frequency:

$$f_c = \sqrt{f_H f_L}$$

The circuit used was the following:

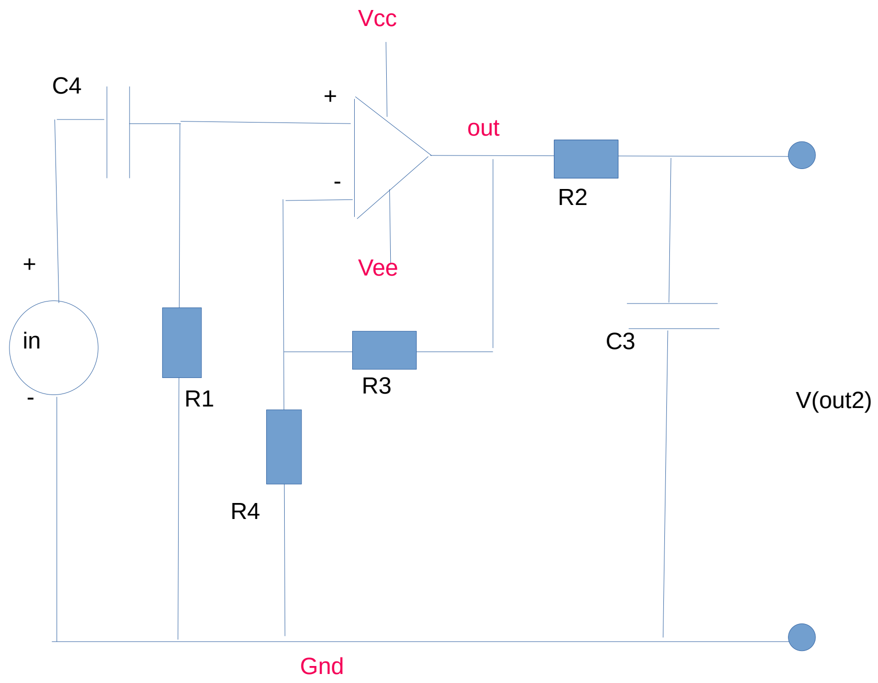

Figure 1: Circuito utilizado

2 Presential Lab

In this lab assigment we were also able to implement this circuit in real life, where we able to measured the gain and the cut-off frequencies. For the circuit configuration, we chose the following components:

R1	R2	R3	R4	C3	C4
1000KΩ	500 Ω	1000KΩ	500 Ω	220nF	220nF

With these components we were able to get a voltage gain of approximately $Gain = 40$ dbs, and cut-off frequencies of $330\,Hz$ and $2.23\,KHz$, corresponding f_L and f_H, respectively. Using ngpsice, we simulated the same circuit, where we obtained the following results:

Cost	13426.472038661
Central frequency, f_0	847.6288757705225
Central frequency deviation $(diff_{F_0})$	152.3711242294775
gain at $1000Hz$, G (db)	42.42502
Gain deviation, $Diff_G$	2.425020000000004
Merit	1.649708859507576e-07
Low Cut off	3.95392e+02
High Cut off	1.81712e+03

3 Theoretical Analysis

3.1 Input and output impedances.

To determine the input and output impedances, we first replace the Op-Amp with its equivalent circuit, as shown in figure (2).

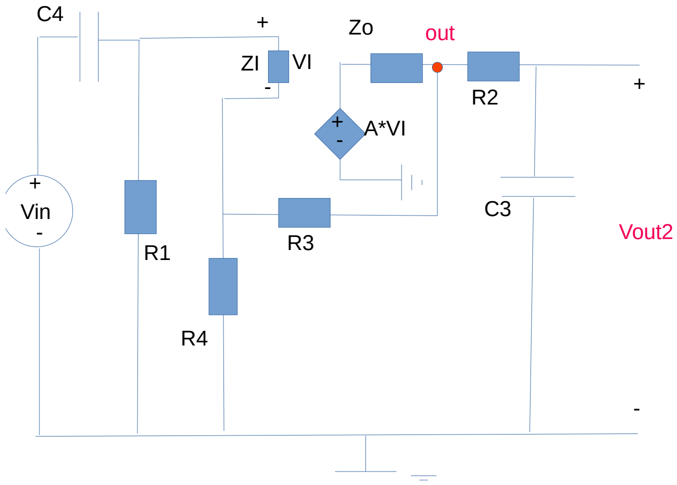

Figure 2: Pass-band circuit, with the amp-pop replaced with its equivalent circuit.

Considering the amp-op configuration is a non-inverting amplifier(and the ideal amp-op model), we get that the output and input impedances, Z_O and Z_I, are 0 and ∞, respectively, and that the gain A is equal to : $(1 + \frac{R_3}{R_4})$. Therefore we get the following circuit, in figure (3)

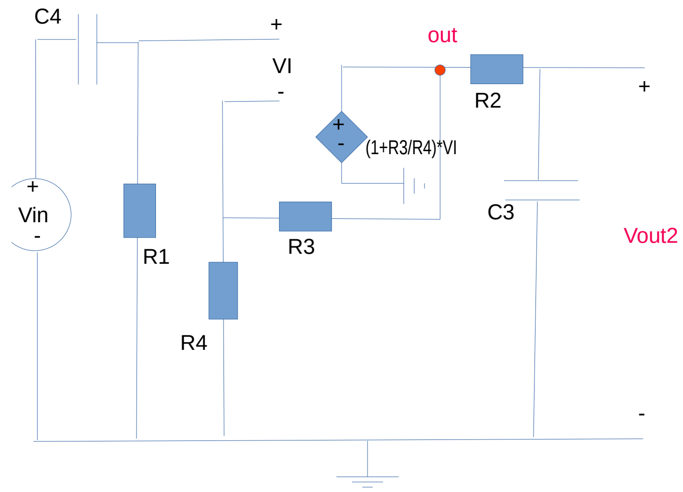

Figure 3: Pass-band circuit, with the amp-pop replaced with its equivalent circuit, using the ideal model aproximation.

Finally, we can deduce the expressions for the input and output impedances for the circuit, Z_I and Z_{0ut}, (as seen by V_{in} and V_{out}, respectively). From the circuit in figure (3), we get that (there is no effect on the first part of the circuit, by V_{out2}, therefore it is not required to short-circuit the output):

$$Z_I(\omega) = Z_{C_4} + R_4 = \frac{1}{j\omega C_4} + R4 \tag{1}$$

As for the output impedance, we need to short-circuit the input, hence we get the circuit in figure (4), from the V_{out_2} terminals:

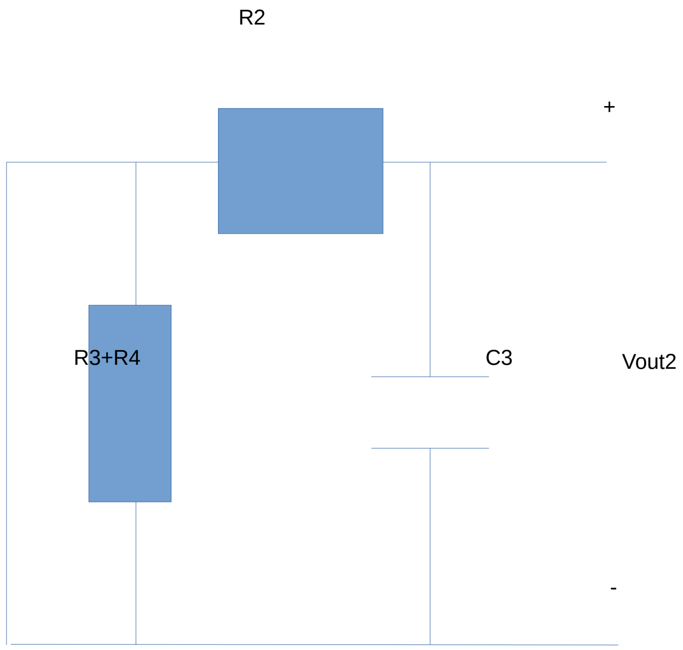

Figure 4: Equivalent circuit seen by the terminals of V_{out_2}, when $V_I = 0$.

Therefore we get that:

$$Z_O(\omega) = R_2||C_3 = \frac{R_2}{j\omega C_3 R_2 + 1} \tag{2}$$

,

3.2 Transfer function

The transfer function is defined as the ration between the output and the input. In our case, the output is $v0$ and the input vs:

$$T(s) = \frac{v0}{vs}$$

after a little algebra, we get to the following expression:

$$T(s) = \frac{R_1 C_1 s}{1 + R_1 C_1 s}(1 + \frac{R_3}{R_4})(\frac{1}{1 + R_2 C_2 s}) \tag{3}$$

where, as usual

$$s = j\omega$$

3.3 Cut-off frequencies

The theoretical cut-off frequencies, f_L and f_H, can be calculated by the Short Circuit Time Constants Method. They are given by[1]:

$$f_L = \frac{1}{R_1 C_1} \tag{4}$$

$$f_H = \frac{1}{R_2 C_2} \tag{5}$$

where f_H is the hight cut-off frequency and f_L is the low cut-off frequency. Experimentally, the cut off frequencies will be calculated through the following expression:

$$f = \frac{V_{max}}{\sqrt{2}}$$

where f can be either f_H or f_L.

The Results obtained using octave were the following:

Total Cost	13427.69537166100
Central Freq	712.82860548662
Central Frequency diference	287.17139451338
Gain	39.72250000000
Cut off low	218.11200000000
Cut off high	2329.65000000000
Gain Diference	0.27750000000
Merit	0.00000097467

Table 1: Values used as parameters for the circuit studied.

[1] If you want to see the deduction in detail, you may visit the following link: `https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-012-microelectronic-devices-and-circuits-fall-2009/lecture-notes/MIT6_012F09_lec23.pdf?fbclid=IwAR3ezEOiIWVJOLyNLNp49EwgcpWSC-_IQFO6wASvf9cKXiGx2_0zBplPnb8`

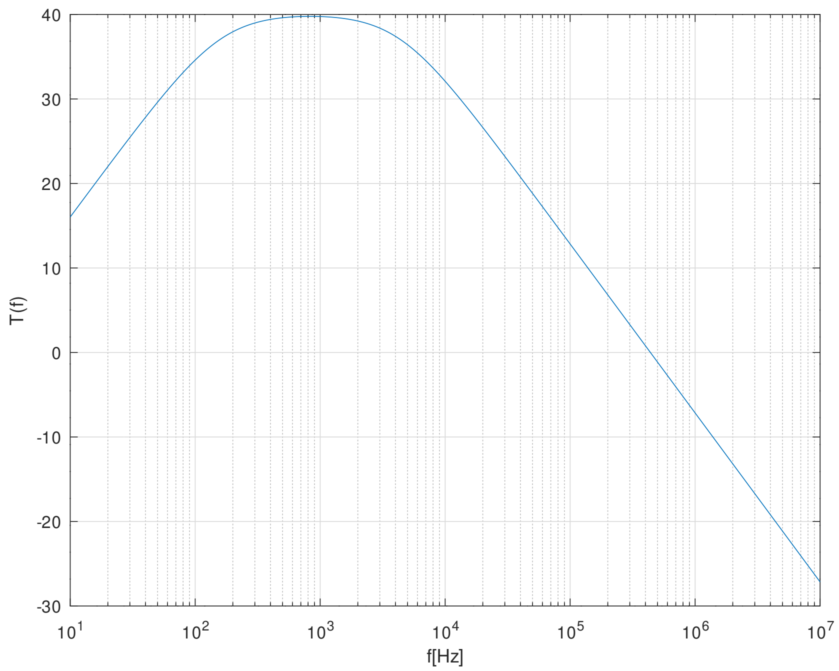

Figure 5: Forced sinusoidal response.

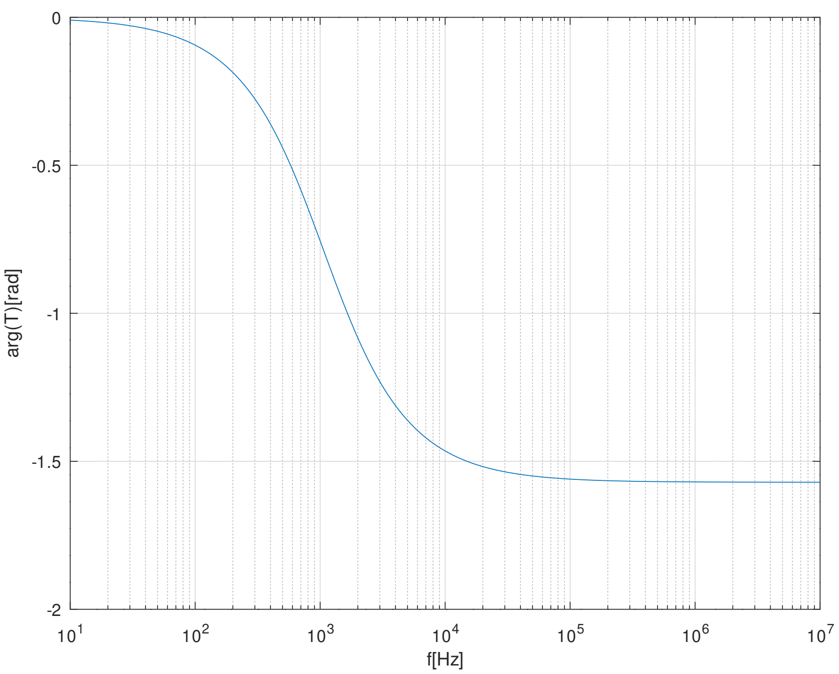

Figure 6: Forced sinusoidal response.

4 Simulation Analysis

The Operating point analysis is the following:

The graphs are the following:

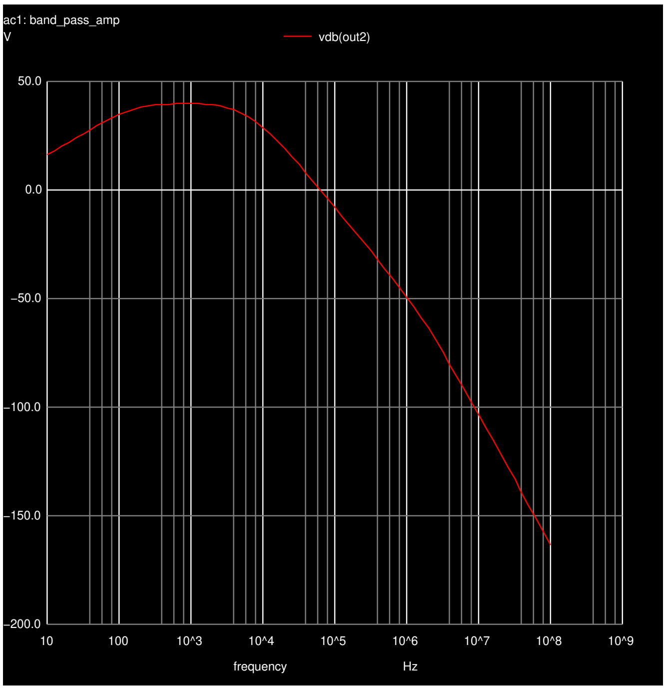

Figure 7: Time analysis

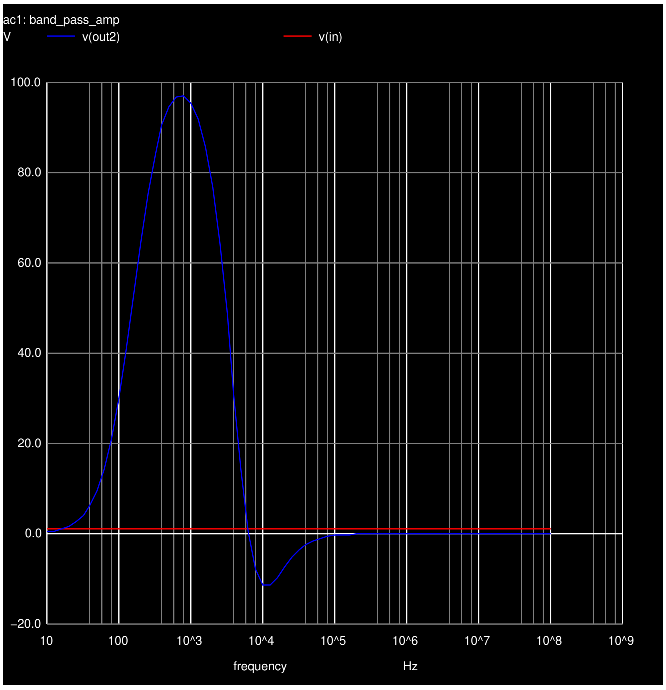

Figure 8: Frequency analysis

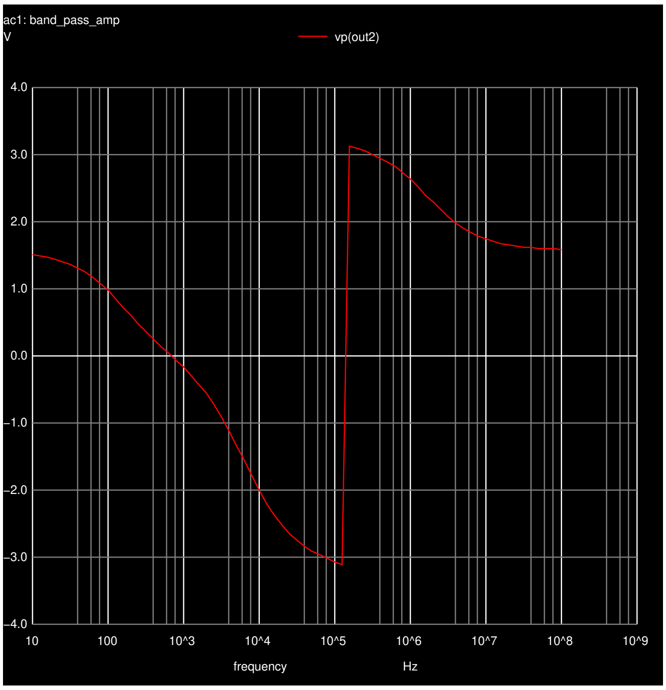
ac1: band_pass_amp
V
vp(out2)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
frequency
Hz

Figure 9: —-

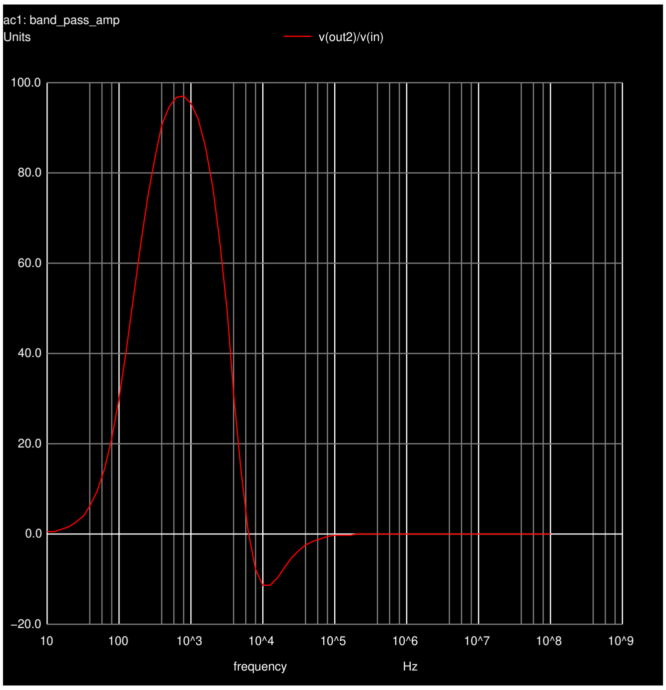

Figure 10: v(out)/v(in)

5 Conclusion