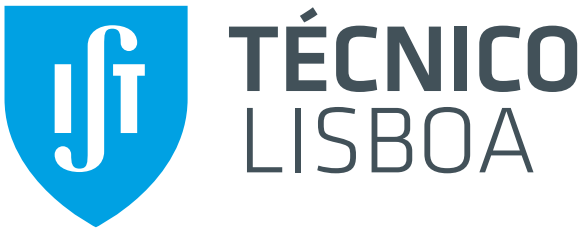
Circuit Theory and Electronics Fundamentals

Instituto Superior Técnico, University of Lisbon



Laboratory 4

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1 Introduction

The objective of this laboratory assignment is to design an Audio Amplifier circuit, using the knowledge we have acquired in the theoretical classes (lecture 16 and 17). We were free to choose the architecture of the Gain and Output amplifier stages. The primal objective was to create an Audio Amplifier circuit with the highest possible merit figure.

This Merit Figure is given by:

$$M = \frac{VoltageGain \times BandWidth}{Cost \times LowerCutOffFrequency} \tag{1}$$

cost = cost of resistors + cost of capacitors + cost of transistors
cost of resistors = 1 monetary unit (MU) per kOhm
cost of capacitors = 1 MU/μF
cost of transistors = 0.1 MU per transistor

The circuit as is shown in the image below is composed by an independent Voltage Source V, a resistor R_s, a Gain Stage, a Output Stage and a Speaker. The circuit can be seen in Figure 1.

In Section 3, a theoretical analysis of the circuit is presented. In Section 2, the circuit is analysed by simulation, and the results are compared to the theoretical results obtained in Section 3.The conclusions of this study are outlined in Section 6.

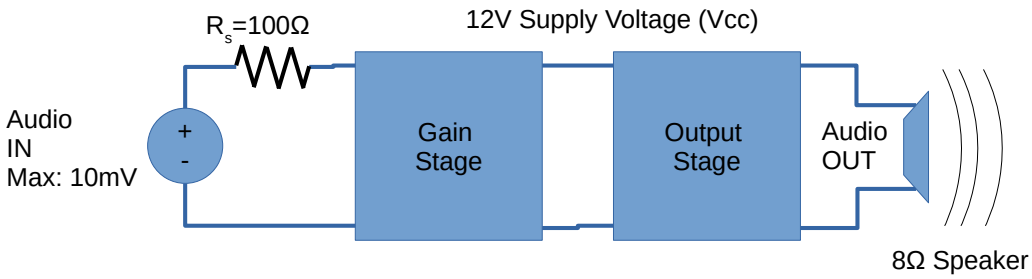

Figure 1: Audio Amplifier

2 Simulation Analysis

2.1 Audio Amplifier Circuit

The objective of this laboratory assignment is to design an Audio Amplifier circuit, using the a Gain Stage and Output Stage. The Gain Stage objective is to increase the gain, and the output stage purpose is to decrease the output impedance.

2.2 Input Signal

The entry signal was computed as a sinusoidal Voltage Source with an amplitude of 10 mV. Besides that, a resistor was implemented to make the simulation behaviour more similar to the real one.

2.3 Gain Stage

The objective of the Gain Stage, as is stated in the name, is to amplify the input signal. With this objective in view, the circuit shown below was implemented:

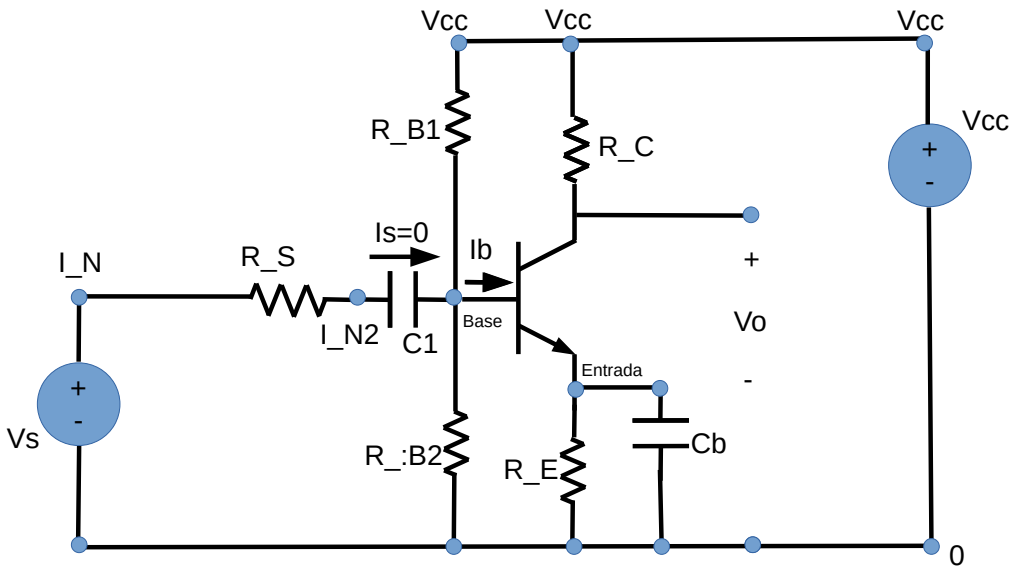

Figure 2: Implemented Gain Stage

Each component has the value shown in the next table:

Name	Value [V], [Ω], [mF]
VT	0.025000
BFN	178.70
VAFN	69.700
RE1	100
RC1	400
RB1	50000
RB2	50000
VBEON	0.70000
VCC	12
RS	100
C1	1
Cb	10

Table 1: Values of the components and transistor parameters

In the the next subsections, the importance of each component will be explained.

2.3.1 Resistor C - R_C

The gain will be completely dependent on R_C, since it will depend on the parallel of R_C and r_o. Since R_C has a much lower value, it will be the paramount parameter in the gain.

2.3.2 Coupling Capacitor - C_I

The Coupling Capacitor has the objective off blocking the DC component of the entry signal. That is, with low frequencies this component behaves as an open circuit, it effectively cuts the DC component. The AC component is not affected, because with high frequencies, it behaves like a short-circuit.

2.3.3 Bias Circuit - V_{cc}, R_{B1} and R_{B2}

The purpose of this component was to ”feed” the transistor, by determining the Base Voltage and ensuring that the BEJ transistor is ON.

2.3.4 Resistor and bypass Capacitor - R_E and C_E

The function of R_E in the circuit is essentially the stabilization of the temperature effect and makes the gain independent of the temperature. However, it has the reverse effect of lowering the gain. To counteract this drop in gain, a bypass capacitor is placed in parallel with the resistance. Thus, we obtain the following behavior:

DC - temperature stability is most important - C_E is a open circuit, R_E stabilizes the temperature effect.

AC - Gain is the most important - C_E is a short-circuit, gain does not drop.

In this way, we are able to achieve both objectives, without significant losses.

2.3.5 Output impedance

Although we have have obtain a good gain , the output impedance was far to big, so with the speaker with an 8 Ohms internal resistance, the signal would be attenuated and we would not reach the proposed objective.

2.3.6 Results on Gain stage

With this circuit and this components we obtained the following behaviors at the output of the Gain Stage:

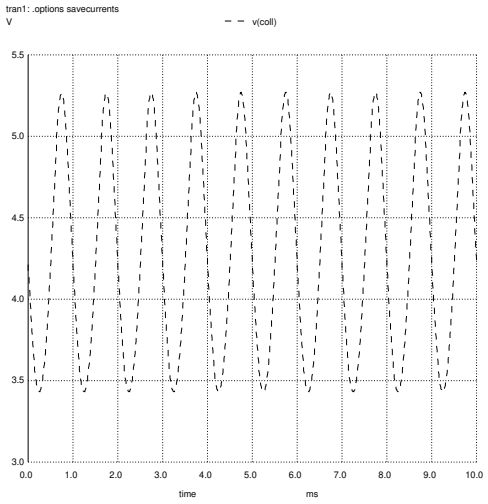

Figure 3: Gain Stage Output signal

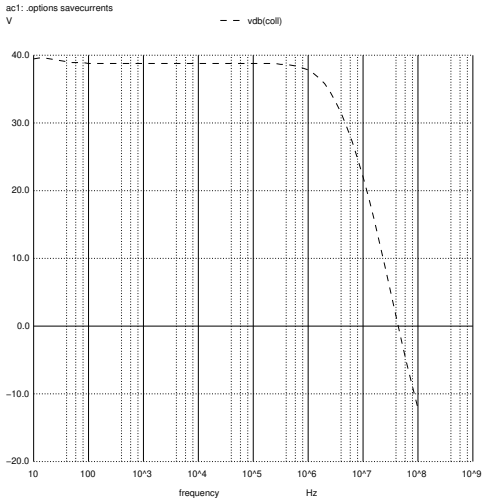

Figure 4: Gain Stage Output Gain

2.4 Output Stage

The purpose of the Output Stage was to put an output impedance low enough so that the entire voltage gain would go to the audio speaker instead of getting lost in one of the resistors. In this way, it is intended that the gain stays approximately unchanged and that the output impedance has a value of at least one order of magnitude below the loudspeaker resistance. In the figure below we show the circuit configuration and its components. in the following table we present the values of each component.

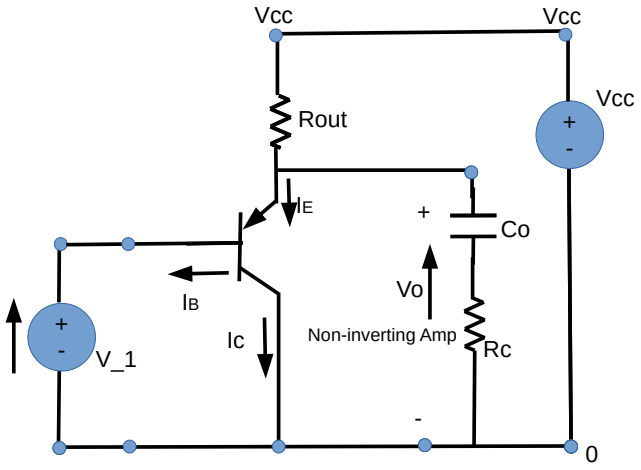

Figure 5: Output stage developed

Name	Value [V], [Ω], [mF]
BFP	227.30
VAFP	37.200
RE2	100
VEBON	0.70000
Rout	100
Co	1

Table 2: Values of the components and transistor parameters

2.4.1 Output Capacitor - C_O

As it was expressed before, this Capacitor's purpose is to block the DC component and allow the passage of the AC component.

2.4.2 Gain

The second objective of this stage is to maintain the Gain value. That is, to make this stage have a gain very close to one. This objective was achieved, as can be seen in the side by side comparison, between the gain and output stage outputs.

2.5 Input and output impedance

One of the fundamental points in our amplifier is that the input impedance must be much greater than the resistance of the signal source, so that, when the voltage division occurs, there are no significant losses. The other point is that the output impedance must be as low as possible compared to the resistance of our speaker, so that, once again, when the split of our output signal will occur, it goes almost entirely to the audio speaker.

In this way we were able to calculate these two circuit parameters.

2.5.1 Input Impedance

To compute the input impedance, we have calculated the resistance that is ”seen” by the signal source. In this way, we divide the voltage at the output of the signal source resistance, for the current that passes in that branch:

$$Z_i = \frac{V(i_{n2})}{I(R_S)} \tag{2}$$

We calculated this value for a frequency that is within the bandwidth interval. We also made the plot of the input impedance in relation to the frequency. We easily conclude that the impedance value in the bandwidth region is constant.

Name	**Value [$k\Omega$]**
ZI	0.0010612

Table 3: Values of Input impedance

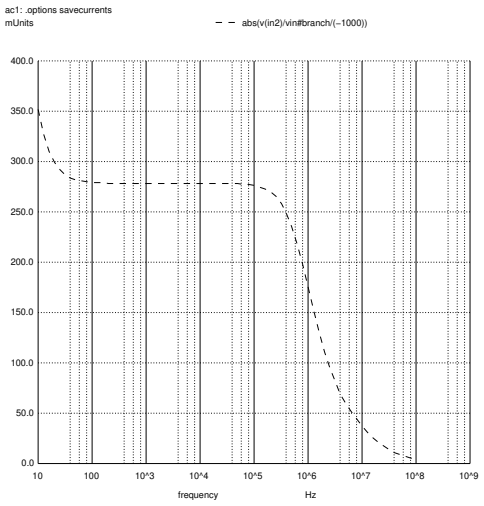

Figure 6: Zi in function of frequency

2.5.2 Output Impedance

To compute the output impedance, we only used the output stage. This can be done because there is no retroactivity, so the Z_O of the output stage is almost equal to the Z_O of the hole circuit. We proceeded in a similar way: first we turned off the signal source, then we put a voltage source in the place of the speaker resistance, and from the voltage and current in that branch, we determined the Z_O. Also, as in the input, we made the plot in function of the frequency. We quickly notice that Z_O is minimal and constant in the bandwith. This is in accordance with the gain behavior, which increases when the Z_O is smaller, that is, the voltage divider causes most of the signal to go to the load resistance.

$$Z_O = \frac{V(out)}{I(out)} \tag{3}$$

Name	**Value [$k\Omega$]**
ZO	0.27431

Table 4: Value of output impedance

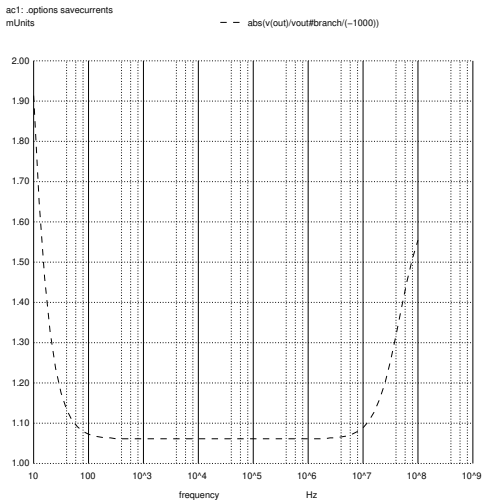

Figure 7: Output impedance in function of frequency

2.6 Final Result

After the two stages were connected, the simulated behavior was the one expected, that is, the signal was amplified and was not distorted:

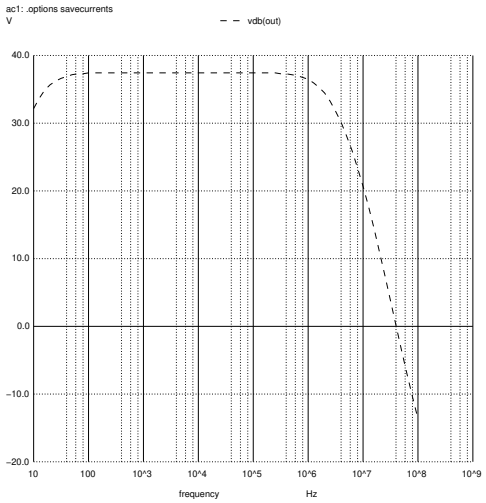

Figure 8: Audio amplifier Gain

With the important data for this lab to be the data shown below:

Name	**Value [dB] [Hz]**
vdboutmax	3.744713e+01
freql	1.480389e+01
frequ	1.981780e+06
frequ - freql	1.981765e+06
vdboutmax * (frequ - freql) / freql	5.012967e+06

Table 5: Values of interest

The Gain was determined from the maximum value of the gain as a function of frequency plot. The lower and upper cutoff frequencies were determined from the find function, when the gain dropped by 3dB in relation to the maximum.

3 Theoretical Analysis

In this section, we used a suitable theoretical model that was able to estimate the gain and the output and input impedances of the two stages.

3.1 Gain Stage

In this subsection we're going to explain how we analysed, theoretically, this stage and, also, how we calculates the important parameters.

3.1.1 OP Analysis

In the operating point analysis we used the Thevenin's equivalent to facilitate its analyses. The circuit is shown in the figure below.

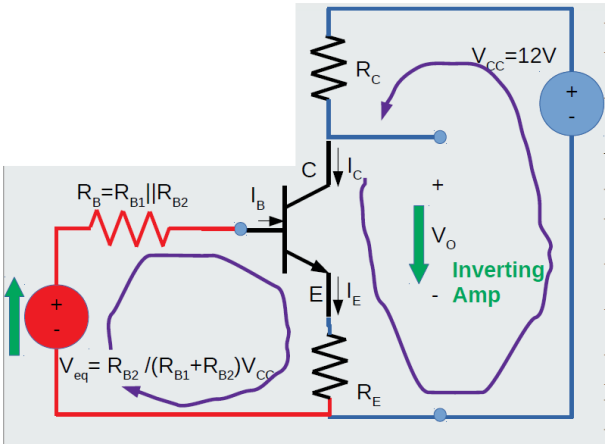

Figure 9: Gain stage circuit (from lecture 17 TCFE)

The important values are computed resorting the following equations:

$$R_B = \frac{R_B1}{R_B1 + R_B2} \tag{4}$$

$$-V_eq = \frac{R_B2}{R_B1 + R_B2} \times V_CC \tag{5}$$

$$V_eq + R_B \times I_B + V_BEON + R_E \times I_E = 0 \tag{6}$$

$$I_E = (1 + \beta_F) \times I_B \tag{7}$$

$$I_B = \frac{V_eq - V_ON}{R_B + (1 + \beta_F) \times R_E} \tag{8}$$

$$I_C = \beta_F \times I_B \tag{9}$$

$$V_O = V_CC - R_C \times I_C \tag{10}$$

$$V_E = R_E \times I_E \tag{11}$$

$$V_C E = V_O - V_E \tag{12}$$

Incremental parameters:

$$g_m = \frac{I_C}{V_T} \tag{13}$$

$$r_\pi = \frac{\beta_F}{g_m} \tag{14}$$

$$r_o \approx \frac{V_A}{I_C} \tag{15}$$

with:

$$V_B EON \approx 0.7V \tag{16}$$

$$\beta_F = 178.7 \tag{17}$$

$$V_A = 69.7V \tag{18}$$

The results were the following:

Name	**Value [V], [Ω], [A], [S]**
RB	25000.00000
VEQ	6
IB1	0.00012334
IC1	0.022041
IE1	0.022165
VE1	2.2165
VO1	3.1835
VCE	0.96707
gm1	0.88165
rpi1	202.69
ro1	3162.3

Table 6: Values determined

3.2 Incremental Analysis

Through incremental analysis of gain stage, we obtained the following circuit:

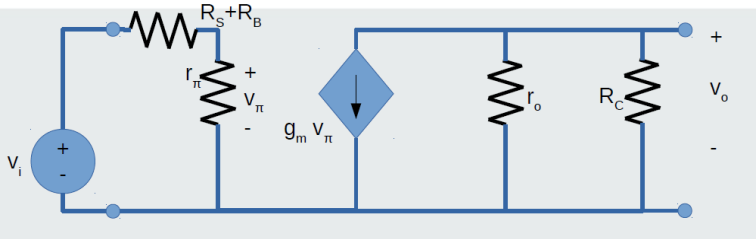

Figure 10: Incremental analysis of gain stage (From lecture 17 TCFE)

In this circuit R_E is canceled by the capacitor bypass. As we are making calculations for our bandwith frequencies, the capacitor already behaves itself like a shortcircuit. We consider $R_E = 0$.

This way, and using the obtained values in the OP analysis, we are able to compute both gain and impedances.

$$\frac{v_o}{v_i} = R_C \times \frac{-g_m \times r_\pi \times r_o}{(r_o + R_C) \times (R_B || R_\pi)} \tag{19}$$

$$Z_I = R_B || R\pi \tag{20}$$

$$Z_O = r_o || R_C \tag{21}$$

From here we obtained the following values for these parameters:

Name	Value [V] [dB] [Ω]
AV1	-315.60
AV1db	115.09
ZI1	201.06
ZO1	355.08

Table 7: Values of average, maximum and minimum voltage and the ripple value

3.3 Output Stage

In this subsection we're going to explain how we analysed, theoretically, this stage and, also, how we calculated the important parameters as we have done to the gain stage.

3.3.1 OP Analysis

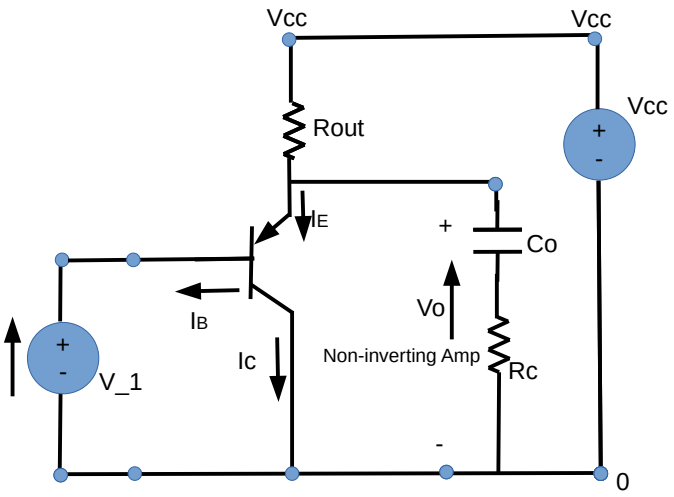

Figure 11: Output stage circuit

The circuit analysis resulted in the following equations and values:

$$R_E \times I_E + V_E BON + V_I - V_C C = 0 \tag{22}$$

$$I_E = \frac{V_C C - V_E BON - V_I}{R_E} \tag{23}$$

$$V_O = V_C C - R_E \times I_E \tag{24}$$

$$V_O = V_I + V_E BON \tag{25}$$

with:

$$V_C C = 12V \tag{26}$$

$$V_E BON \approx 0.7V \tag{27}$$

$$R_E = 100\Omega \tag{28}$$

Name	Value [V] [A]
VI2	3.1835
IE2	0.081165
IC2	0.080809
VO2	3.8835

Table 8: OP values computed

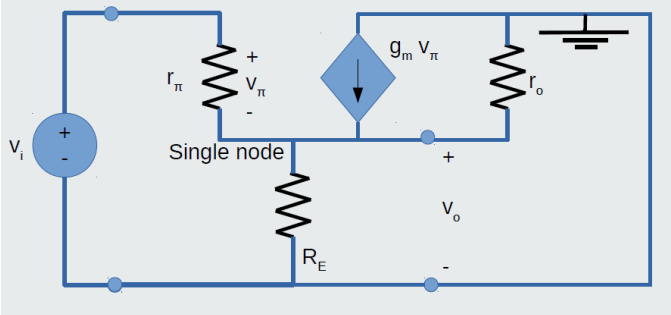

Figure 12: Incremental analysis of de output stage (From lecture 17 TCFE)

3.4 Incremental Analysis

Doing the incremental analysis of the gain stage, we have obtained the following circuit:

The circuit was analyzed in order to obtain the gain and impedances. The equations and values obtained are as follows:

$$g_\pi = \frac{1}{r_\pi} \tag{29}$$

$$g_E = \frac{1}{R_E} \tag{30}$$

$$g_o = \frac{1}{r_o} \tag{31}$$

From KCL,

$$(\frac{1}{R_E} + \frac{1}{r_o}) \times v_o + \frac{v_o - v_i}{r_\pi} - g_m \times v_\pi = 0 \tag{32}$$

$$v_\pi = v_i - v_o \tag{33}$$

which results:

$$\frac{v_o}{v_i} = \frac{g_m}{g_\pi + g_E + g_o + g_m} \tag{34}$$

$$Z_I = \frac{g_\pi + g_E + g_o + g_m}{g_\pi \times (g_\pi + g_E + g_o)} \tag{35}$$

$$Z_o = \frac{1}{g_\pi + g_E + g_o + g_m} \tag{36}$$

Name	Value [V], [dB] and [Ω]
AV2	0.99190
AV2db	-0.16264
ZI2	8682.4
ZO2	0.30686

Table 9: Values of interest computed

As we can see, the values go according to the expected, therefore, we have an unitary gain and an output impedance much lower than the speaker 8 Ω.

4 Side by Side comparison

In this section we are going to analyse and compare the results generated with the Ngspice simulation and with the Octave tool (Theoretical analysis).

The results that we are interested are the gain and the input and output impedances

The theoretical values were:

Name	Value [dB] [Ω]
AVdB	115.09
AV	315.60
ZI	201.06
ZO	0.30686

Table 10: Theoretical values

The simulation values were:

Name	Value [dB] [Ω]
AVdB	37.447
AV	74.534
ZI	274.31
ZO	1.0612

Table 11: Simulation values

As we can see, the theoretical values differ from the simulated ones. The first reason for this is that our theoretical model is a much less accurate approximation of reality than the simulation. Also, the theoretical input impedance is lower because it does not take into consideration the load of the rest of the circuit which, despite being small, it exists. In the output impedance the same is verified. The theoretical value does not take into consideration the resistive load that it was before. For these factors, the value of the theoretical gain will be bigger than the simulated one.

Even so, the impedance values are inside the expected values, which means that we have a good input impedance, a low output impedance (as proposed) and an adequate gain.

5 Figure of merit

The final objective was to obtain a figure of merit as high as possible. In this section, we present the final result, after we performed all the analysis

This Merit Figure is given by:

$$M = \frac{VoltageGain \times BandWidth}{Cost \times LowerCutOffFrequency} \tag{37}$$

cost = cost of resistors + cost of capacitors + cost of transistors
cost of resistors = 1 monetary unit (MU) per kOhm
cost of capacitors = 1 MU/μF
cost of transistors = 0.1 MU per transistor

Finally, we obtained the important values to calculate the Merit Figure, which we present in the table below. The values used were those of the simulation, since they represent a more accurate approximation of reality.

Name	**Value [dB], [Hz] and [MU]**
GAIN	74.534
FREQL	14.804
FREQU	1981780
BANDWITH	1981765
COST	12200.60000
FM	817.81

Table 12: Values of interest and FM

6 Conclusion

In this laboratory assignment, the objective was to implement an Audio Amplifier with the highest Merit Figure as possible (this merit figure depends on the price of the components, the bandwith, the gain and the lower cutoff frequency), using the Octave Math tool and by running a simulation using the Ngspice tool.
In this laboratory we did not obtain the same values in the two analysis. This was due to the fact that the theoretical analysis makes a large number of simplifying approximations when analysing the transistor model, that has a more ideal behaviour than the one that is used on the simulation, because of that in the case of the simulation analysis the values were better than the one computed in the theoretical analysis. To conclude, the objective was achieved, since we built an audio amplifier with good voltage gain and bandwith.