ELEC 301

Mini-Project 2 Report

Sherwin Adrien Tiu

Student #: 35443258

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1. Introduction

This report investigates the methods used for analyzing bipolar junction transistors (BJTs) using three different transistors: 2N2222A, 2N4401, and 2N3904. In this report, we design bias networks for the common emitter amplifier and characterize the response of each amplifier through Analog Device's LTSpice software.

2. Mini Project

Part 1

1A.

The small-signal "h-parameters" h_{fe}, h_{ie}, and h_{oe} of the 2N2222A transistor are found from a datasheet by STMicroelectronics [1], and its minimum and maximum values are listed in table 1. The values are for the following conditions: V_{CE} = 10 V, I_C = 1 mA, f = 1 kHz, and T = 25°C.

Parameter	Description	Min	Max
$h_{fe} = \beta$	Small Signal Current Gain	50	300
$h_{ie} = r_\pi$	Input Impedance	2kΩ	8kΩ
$h_{oe} = 1/r_0$	Output Admittance	5µS	35µS

Table 1. The values of h_{fe}, h_{ie}, and h_{oe}, gathered from [1].

1B.

In this section, we obtain the "measured" values through simulating the circuits in figures 1a, 2a, and 3a in the LTSpice software. For getting the plots, a DC sweep is performed on each circuit, with resulting figures in figures 1b, 2b, and 3b, respectively.

Using the plot in figure 4, and with the value of I_C being 1 mA, the corresponding value for the collector current I_B is 5 µA. Using equation 1, we get the small signal current gain β = 200. At 25°C, the thermal voltage is approximately 25 mV, and using equation 2, the transconductance gain is 0.04 S. The internal resistance r_π from equation 3 is 5000 Ω.

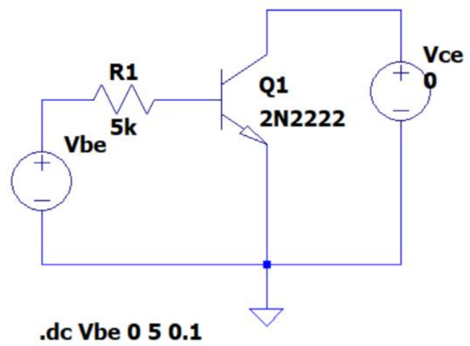

Figure 1a. Circuit diagram for part 1b for plotting I_B vs V_{BE}.

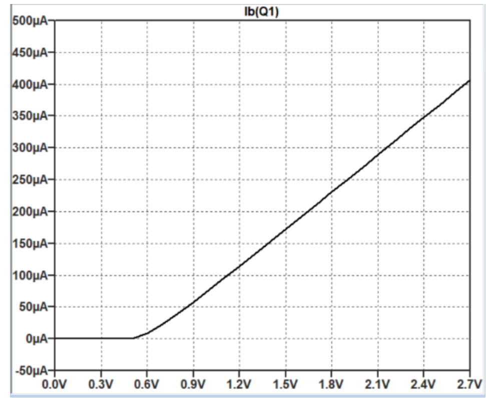

Figure 1b. Plot for I_B vs V_{BE} for part 1b, from the circuit in figure 1a.

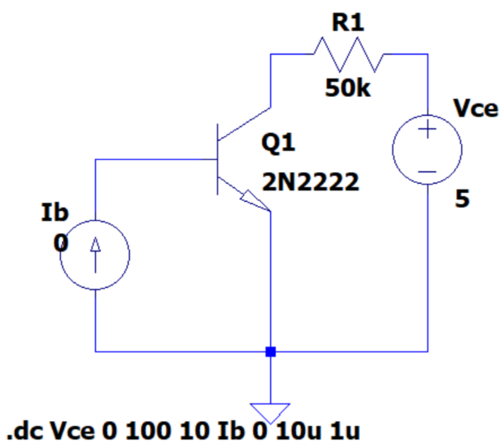

Figure 2a. Circuit diagram for part 1b for plotting I_C vs V_{CE}, with I_B as the variable parameter.

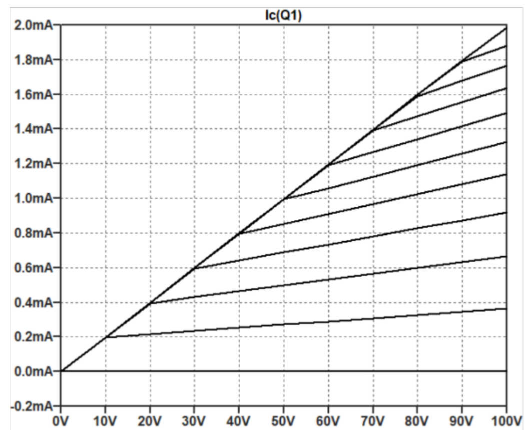

Figure 2b. Plot for I_C vs V_{CE} from circuit in figure 2a. The lowest line (starting at 0.2 mA) represents I_B = 1 µA, incrementing by 1 µA at every line above thereafter.

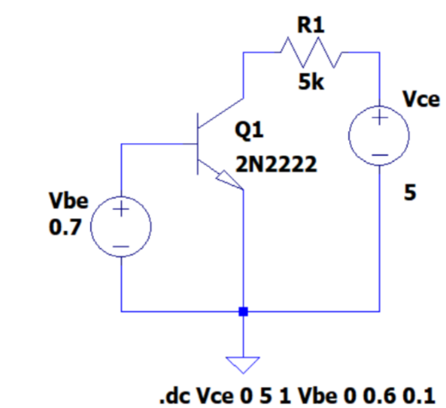

Figure 3a. Circuit diagram for part 1b for plotting I_C vs V_{CE}, with V_{BE} as the variable parameter.

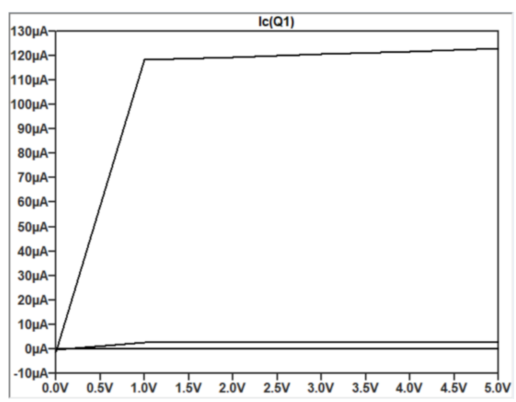

Figure 3b. Plot for I_C vs V_{CE} for part 1b, from the circuit in figure 3a.

Finally, to get r_o, we first find the Early voltage V_A, done by taking two points from a line in figure 4 and extrapolating it to 0 A, giving V_A = 100 V. Using equation 4, r_o = 100 kΩ.

$$I_C = \beta I_B \rightarrow \beta = \frac{I_C}{I_B} = 200 \tag{1}$$

$$g_m = \frac{I_C}{V_T} = 0.04\ S \tag{2}$$

$$r_\pi = \frac{\beta}{g_m} = 5000\ \Omega \tag{3}$$

$$r_0 = \frac{V_A}{I_C} = 100\ k\Omega \tag{4}$$

Comparing the "measured" values to the ones given in the data sheet in table 1, we see that all the calculated values are within the range of values provided in the datasheet.

1C.

To let the 2N2222A transistor bias the circuit using the "measured" values in part 1B, we first compute the emitter current as in equation 5 and through mesh analysis from V_{CC} to the common ground, we get the values of R_C and R_E through solving equation 6. The relation between R_C and R_E can be found in equation 7.

$$I_E = I_B + I_C = 1.005\ mA \tag{5}$$

$$V_{CC} = 15\ V = I_c R_C + I_E R_E \rightarrow R_C = 9.983\ k\Omega\,; R_E = 4.992\ k\Omega \tag{6}$$

$$R_E = \frac{1}{2} R_C \tag{7}$$

The voltages can be found through equations 8, 9, and 10. The value of V_{BE} is 0.6 V, as given in the datasheet [1].

$$V_E = R_E \times I_E = 5.0166\ V \tag{8}$$

$$V_C = V_E + V_{CE} = 10.0166\ V \tag{9}$$

$$V_B = V_E + V_{BE} = 5.6166\ V \tag{10}$$

Using another mesh analysis, we can obtain equation 11, and through Kirchoff's Current Law (KCL), we get equation 12. Through solving equations 11 and 12, we find that the two equations are non-linear, hence the relation between R_{B1} and R_{B2} in equation 13.

$$\frac{R_{B2}}{R_{B1}+R_{B2}} \times V_{CC} = (R_{B1} \,||\, R_{B2}) \times I_B + V_B \tag{11}$$

$$\frac{V_{CC}-V_B}{R_{B1}} = I_B + \frac{V_B}{R_{B2}} \tag{12}$$

$$R_{B2} = \frac{1123320 + R_{B1}}{1876680 - R_{B1}} \tag{13}$$

We set R_{B1} to be 750 kΩ as this is one of the standard resistor values in [2] and choosing a high value for resistance results to less power dissipation. Using equation 13, we get R_{B2} = 747763 Ω ≈ 750 kΩ. Having the same resistor values for both R_{B1} and R_{B2} will be advantageous in that it will make the circuit a little less complex and is more economical when getting the resistors in bulk. The simulated circuit is seen in figure 4a, and the table for the d.c. operating point is provided in table 2.

I_B	I_C	I_E	V_B	V_C	V_E
5.0621 µA	9.8582 mA	0.9909 mA	5.6017 V	5.1585 V	4.9465 V

Table 2. D.C. operating point values for the biassed circuit in figure 4a.

For the 1/3 rule, we use equations 14, 15, and 16 to get the voltages and equations 17, and 18 to get the currents. Equations 14, 15, and 17 are the formula given for using the 1/3 rule [3].

$$V_B = \frac{1}{3} \times V_{CC} = 5\,V \tag{14}$$

$$V_C = \frac{2}{3} \times V_{CC} = 10\,V \tag{15}$$

$$V_E = V_B - V_{BE} = 4.4\,V \tag{16}$$

$$I_1 = \frac{I_E}{\sqrt{\beta}} = 71.0642\,\mu A \tag{17}$$

$$I_2 = I_1 - I_B = 66.0642\,\mu A \tag{18}$$

Equations 19, 20, 21, and 22 were used to find all the resistor values for the circuit in figure 4b. The d.c. operating point values of the circuit are listed in table 3. In figure 4c, the resistors are replaced with standard values from [2] and d.c. operating values listed in table 4.

$$R_C = \frac{1}{3} \times \frac{V_{CC}}{I_C} = 5000\ \Omega \tag{19}$$

$$R_E = \frac{V_E}{I_E} = \frac{\frac{1}{3}V_{CC} - V_{BE}}{I_E} = 4378.11\ \Omega \tag{20}$$

$$R_{B1} = \frac{\frac{2}{3}V_{CC}}{I_1} = 140717.77\ \Omega \tag{21}$$

$$R_{B2} = \frac{V_B}{I_2} = 75683.92\ \Omega \tag{22}$$

I_B	I_C	I_E	V_B	V_C	V_E
4.7322 µA	0.9910 mA	0.9957 mA	5.0132 V	10.0452 V	4.3692 V

Table 3. D.C. operating point values for the biassed circuit in figure 4b.

I_B	I_C	I_E	V_B	V_C	V_E
4.5390 µA	0.9536 mA	0.9582 mA	4.7731 V	10.1365 V	4.1201 V

Table 4. D.C. operating point values for the biassed circuit in figure 4c.

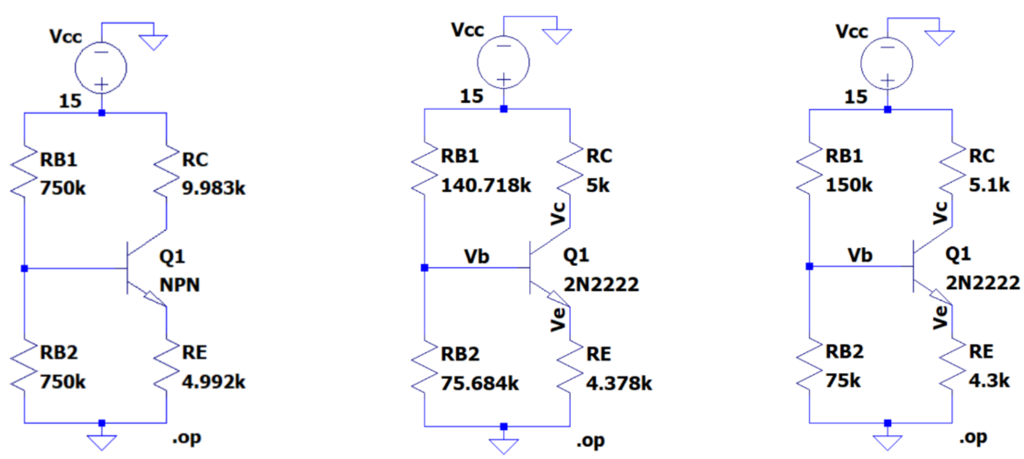

Figure 4. The 2N2222A biassed circuit with calculated resistor values a) using “measured” circuit parameters b) using the 1/3 rule c) using standard resistor values from [2].

The use of the 1/3 rule or the lack thereof still resulted in a circuit that is properly biassed. However, the 1/3 rule allows for quick calculation of resistances, and comparing tables 3 and 4 does not give a significant difference after swapping to standard resistors. This shows the versatility afforded by the 1/3 rule.

1D.

Now, replacing the transistor in figure 4c with 2N3904 (table 5A) and 2N4401 (table 5B), we get their d.c. operating point values.

	I_B	I_C	I_E	V_B	V_C	V_E
A	3.0866 µA	0.9719 mA	0.9750 mA	4.8457 V	10.0435 V	4.1923 V
B	7.7005 µA	0.9198 mA	0.9275 mA	4.6150 V	10.3091 V	3.9882 V

Table 5. D.C. operating point values for the A) 2N3904 and B) 2N4401 transistors.

The only significant difference seen in table 5 would be the I_B and this is so because the calculation for that current using the 1/3 rule depends on the transistor's small signal parameters. Other than that, we can see that the two circuits are still properly biassed and shows that the 1/3 rule is a valid method of biassing BJTs, even with different β values.

Part 2

2A.

To find the calculated values, we start with the low frequency response. Due to the presence of coupling capacitors C_{C1} and C_{C2} in the circuit in figure 5, the zeroes ω_{Lz1} = ω_{Lz2} = 0. The third low-frequency zero can be computed as:

$$\omega_{Lz3} = \frac{1}{R_E \times C_E} = 23.256 \frac{rad}{s} = 3.701\ Hz \tag{23}$$

Using the formulas given in [3], the low and high-frequency poles are:

$$\omega_{Lp1} = \frac{1}{(R_C + R_L) \times C_{C2}} = 9.804 \frac{rad}{s} \rightarrow f_{Lp1} = 1.560\ Hz \tag{24}$$

$$\omega_{Lp2} = \frac{1}{(R_S + R_{BB}||(r_\pi + (1+\beta) \times R_E)) \times C_{C1}} = 2.113 \frac{rad}{s} \rightarrow f_{Lp2} = 0.336\ Hz \tag{25}$$

$$\omega_{Lp3} = \frac{1}{(R_E|| \frac{r_\pi + R_{BB}||R_S}{1+\beta}) \times C_E} = 3980.238 \frac{rad}{s} \rightarrow f_{Lp3} = 633.475\ Hz \tag{26}$$

$$\omega_{Hp1} = \frac{1}{(R_{BB}||r_\pi)||(R_S(C_\pi + C_\mu(1 + g_m(R_C||R_L))))} = 33.238 \frac{Mrad}{s} \rightarrow f_{Hp1} = 5.273\ MHz \tag{27}$$

$$\omega_{Hp2} = \frac{1}{(R_C||R_L) \times C_\mu} = 75.297 \frac{Mrad}{s} \rightarrow f_{Hp2} = 11.984\ MHz \tag{28}$$

where R_{BB} is defined as:

$$R_{BB} = R_{B1}||R_{B2} \tag{29}$$

The values of the estimated and the calculated pole and zero locations are in table 6.

	f_{Lz1}	f_{Lz2}	f_{Lz3}	f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hz1}	f_{Hp1}	f_{Hp2}
Calculated	0	0	3.70	1.56	0.40	633	-	5.27M	12.0M
Estimated	0	0	4.34	1.83	0.33	623	1.73G	3.71M	112M

Table 6. Calculated and graphically estimated pole and zero locations of the circuit for the 2N4401 transistor. All values are in Hz.

As seen in table 6, there is a significant difference in values for the high-frequency poles. Since we are using a few approximations when we calculated for our high-frequency poles, such as small-signal analysis and the Miller Theorem, we can expect our calculations for those values to be inaccurate.

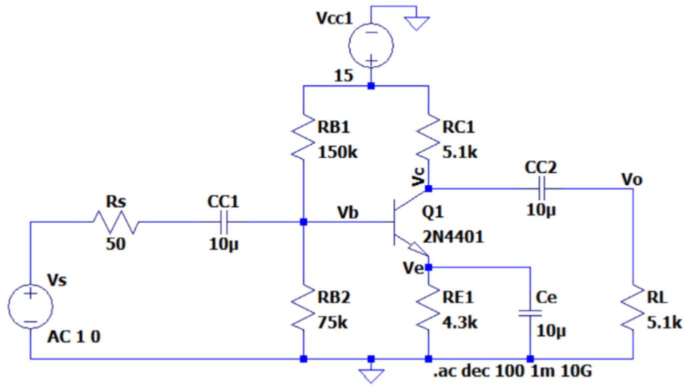

Figure 5. The simulated circuit for part 2a. A similar circuit, replacing the 2N4401 transistor with the 2N3904 transistor, was simulated for part 3a.

For determining the locations of zeroes and poles graphically, we use linear approximations and find the intersection of the slopes. These approximations are seen as the dashed lines in figure 6.

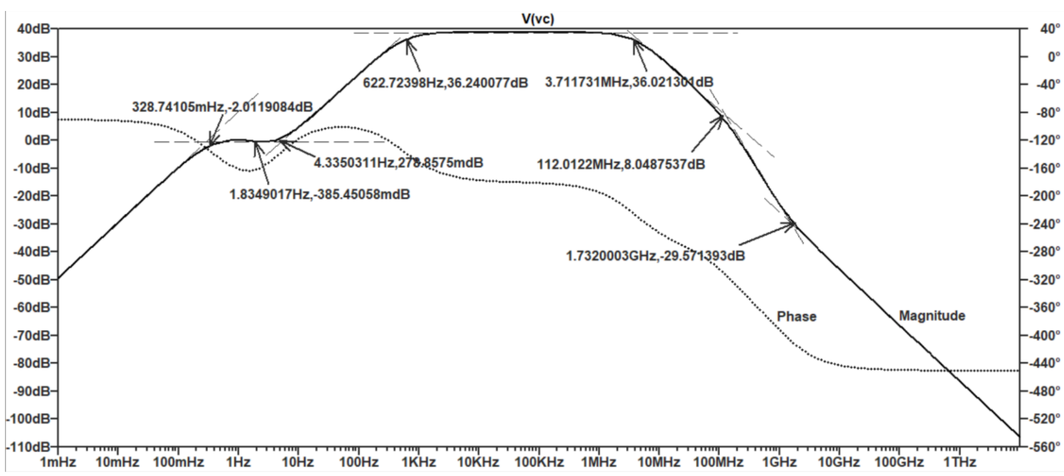

Figure 6. The magnitude and phase plots of the circuit in figure 5. The graphically estimated pole and zero locations are labelled in the figure.

2B.

For the midband frequency, we choose 100 kHz. Through varying V_s between 0 and 60 mV, we get the voltage transfer curve, figure 7. From this plot, we observe that the cut-off voltage is 40 mV.

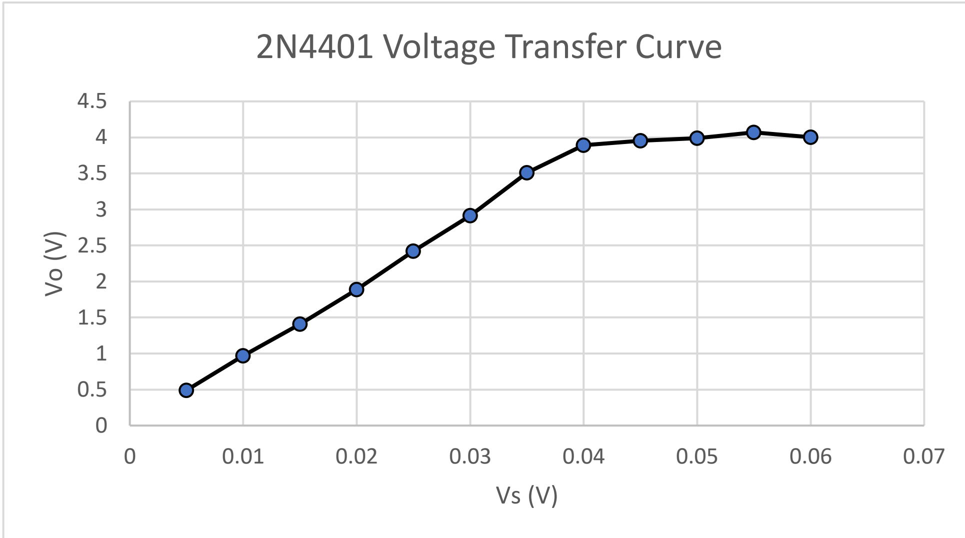

Figure 7. Voltage transfer curve of the circuit with 2N4401 transistor.

2C.

To calculate the input impedance Z_{in}, we use equation 30. For the simulated values, we set the AC source to 100 kHz and with an amplitude of 1V. The simulated input impedance can be found in equation 31.

$$Z_{in} = R_{BB}||r_\pi = 4583\ \Omega \tag{30}$$

$$Z_{in} = \frac{V_B}{I_{in}} = 4453\ \Omega \tag{31}$$

2D.

To get the calculated output impedance, we use $R_C = Z_{out} = 5.1\ k\Omega$. For the simulated output impedance, we use equation 32.

$$Z_{out} = \frac{V_O}{I_{out}} = 5.096\ k\Omega \tag{32}$$

2E.

Comparing the 2N4401 and the 2N3904 transistors, we choose the 2N3904 transistor. As we are looking for better amplifiers, we prefer one with a wider bandwidth so to give a better performance. And since 2N3904 offers a wider bandwidth compared to the 2N4401 transistor, and with differences between the various calculated characteristics of the two transistors not very significant, we should select the 2N3904 transistor. The various calculations can be found in Part 3 of the report.

Part 3

For this part, we are finding various characteristics associated with the common base amplifier using the 2N3904 transistor [4].

3A.

Like what had been done in part 2A, we use equations 23 to 28 to get the pole and zero locations for the circuit with a 2N3904 transistor. All the calculated and graphically estimated values can be found in table 7.

	f_{Lz1}	f_{Lz2}	f_{Lz3}	f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hz1}	f_{Hz1}	f_{Hp1}	f_{Hp2}
Calculated	0	0	3.70	1.56	0.42	591	-	-	15.2M	34.9M
Estimated	0	0	4.20	1.89	0.34	603	2.70G	67.4G	6.80M	341M

Table 7. Calculated and graphically estimated pole and zero locations of the circuit for the 2N4401 transistor. All values are in Hz.

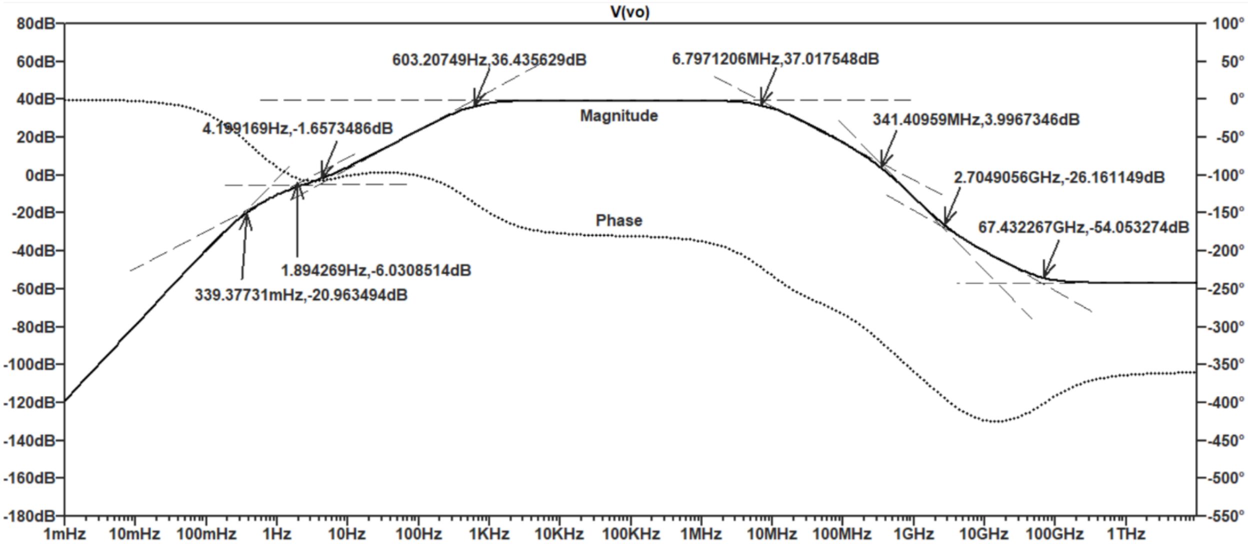

Figure 8. Magnitude and phase Bode plots of the 2N3904 circuit, similar to Figure 5.

3B.

Using a similar procedure as in part 2B, we get the voltage transfer curve for the circuit with a 2N3904 transistor. Like figure 7, we can see the cut-off voltage to be 40 mV.

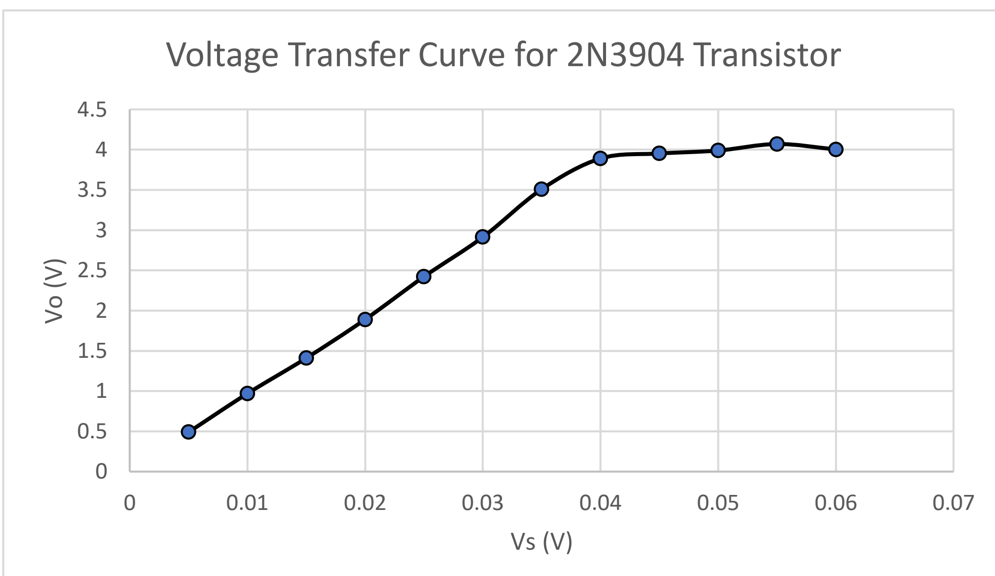

Figure 9. Voltage transfer curve of the circuit with 2N4401 transistor.

3C.

From equation 30, we get Z_{in} = 2863 Ω for the calculated and from equation 31, we get Z_{in} = 3247 Ω for the simulated.

3D.

The calculated output impedance for the 2N3904 remains the same as from 2N4401. The procedure for calculating the simulated value remains the same as in part 2D, with Z_{out} = 5.110 kΩ from equation 32.

3. Conclusion

In this project, we learned how to model, bias, analyze, and test various transistors. We determined that the 1/3 rule can be a quick, easy way to get resistance values that can correctly bias a circuit, even after swapping these values with the standard resistor values in the market. Lastly, we learned to compare various amplifiers and choose the best one based on the need.

4. References

[1] STMicroelectronics 2N2219A, 2N2222A Datasheet

[2] ELEC 301 Standard Resistor and Capacitor Values Sheet

[3] ELEC 301 Course Notes

[4] ELEC 301 Mini Project 2 Handout

[5] LTSpice™ User Manual

[6] A. Sedra and K. Smith, "Microelectronic Circuits," 5th (or higher) Ed., Oxford University Press, New York.