Mini Project 2

ELEC 301

pgoel125@student.ubc.ca
90300815

Contents

Introduction 1
Problems 2
PART 1 2
PART 2 6
PART 3 11
Conclusion 13
References 14

Table of Circuits

Circuit 1 ________ *2*
Circuit 2 ________ *3*
Circuit 3 ________ *3*
Circuit 4:Bias Network for npn transistor ________ *4*
Circuit 5: 1/3 Rule Bias ________ *5*
Circuit 6: Bias Circuit for 2N3904 and 2N4401 ________ *6*
Circuit 7: Common Emitter Amplifier ________ *6*
Circuit 8: High frequency small-signal model ________ *7*
Circuit 9:Common Base Amplifier ________ *11*

Table of Plots

Plot 1: I_B v/s V_{BE} ________ *2*
Plot 2: I_C v/s V_{CE} with variable I_{BN} ________ *3*
Plot 3: I_C v/s V_{CE} with variable V_{BE} ________ *3*
Plot 4:Phase (degrees) Bode Plot ________ *7*
Plot 5:Magnitute Bode Plot ________ *7*
Plot 6: Linear Interpolation for Measuring poles and zeros ________ *8*
Plot 7: Phase Bode Plot for 2N4401 ________ *8*
Plot 8:Magnitude Bode Plot for 2N4401 ________ *8*
Plot 9: Transfer Curve for 2N4401 ________ *9*
Plot 10: Transfer Curve for 2N3904 ________ *9*
Plot 11: Phase Bode Plot for CB Amplifier ________ *11*
Plot 12: Magnitude Bode Plot for CB Amplifier ________ *11*
Plot 13: Transfer Curve for 2N2222A ________ *12*

Introduction

The aim of this project report is to detail the modeling of bipolar junction transistors that are intended for small signal operation using a hybrid-π model. Specifically, two basic single transistor amplifier circuits, namely the common emitter and common base amplifiers, will be examined. It is important to note that the analysis is conducted under the assumption of small signals, as larger signals can cause the transistors to enter saturation or cut-off modes, where the hybrid-π model is no longer applicable. The project employs three different types of transistors, namely 2N2222A, 2N3904, and 2N4401, and their datasheets were sourced from the manufacturers' websites.

Problems

PART 1

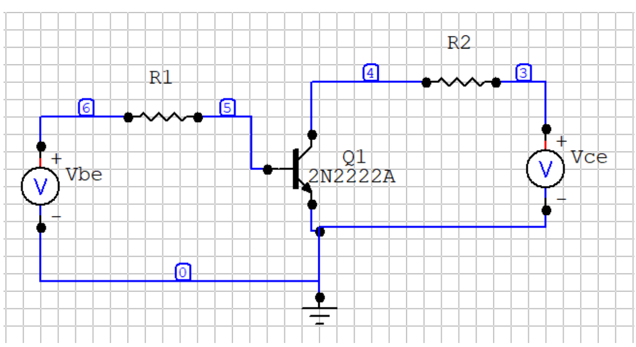
A. **Small Signal Parameters**

The values of the small signal parameters for V_{CE} = 10V, I_C = 1 mA, f = 1kHz and T = 25˚C are,

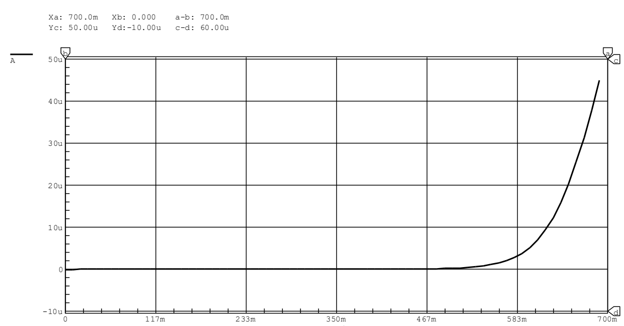
Parameter	Min	Max
$\boldsymbol{h_{fe}}$	50	300
$\boldsymbol{h_{ie}}$	2 kΩ	8 kΩ
$\boldsymbol{h_{oe}}$	5 µS	35 µS

B. **Calculation of hybrid- π Model Parameters**

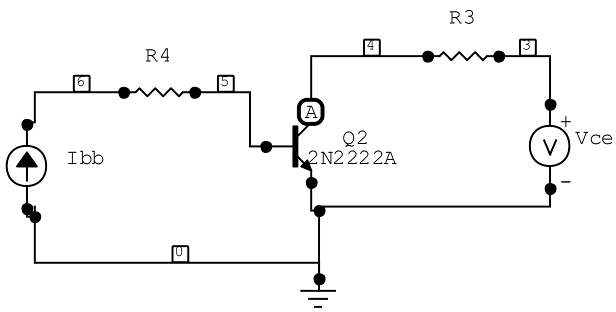
Using *CircuitMaker* and the Circuits given below to plat the graphs to obtain the values



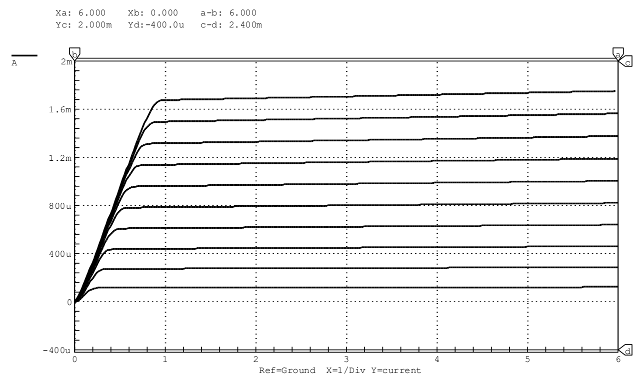
Circuit 1



Plot 1: I_B v/s V_{BE}

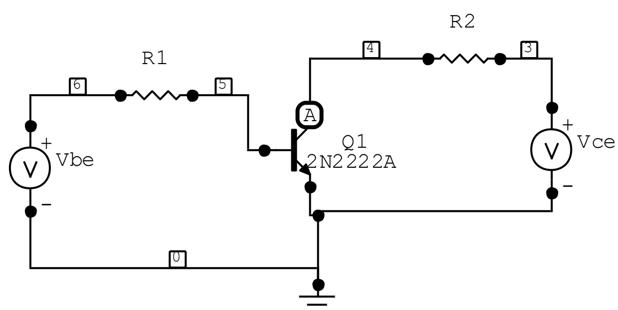


Circuit 2

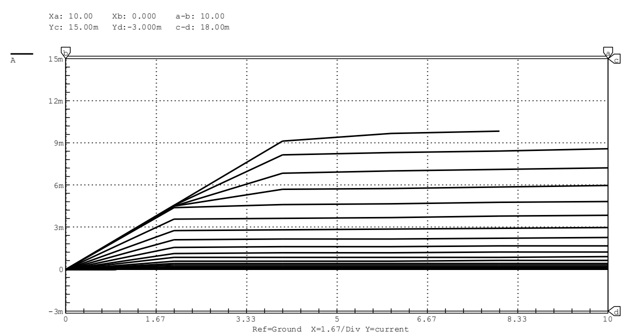


Plot 2: I_C v/s V_{CE} with variable I_{BN}

In I_c vs V_{CE} plot, variable $I_B = 1\mu A$ increments, with top increment $I_B = 10\ \mu A$.



Circuit 3



Plot 3: I_C v/s V_{CE} with variable V_{BE}

For the calculation of β, r_π, gm, and r_0 for $V_{CE} = 5$ V and $I_c = 1$mA.

From Plot 2, at given data $I_B = 6\ \mu A$. Since $I_c = \beta I_B$,

$$\beta = 166.7$$

$$g_m = \frac{I_C}{V_T} = \frac{1\ mA}{25\ mV} = 0.040S$$ | Given that $V_T = 25$ mV at T = 25 ˚C

$$r_\pi = \frac{\beta}{g_m} = \frac{166.7}{0.040} = 4167\Omega$$

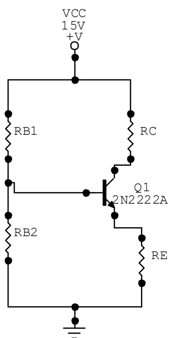
Next, for r_o we can estimate V_A by calculating the slope of active region at $I_B = 8\ \mu A$

$$m_{8\ \mu A} = \frac{(1.4207 - 1.327)\ \text{mA}}{(8.333 - 1.667)V} = \frac{(1.4207 - 0)\ \text{mA}}{(8.333 - V_A)\ V}$$, Therefore $V_A = -108.922\ V$

Thus $r_o = \frac{V_A}{I_C} = \frac{108.922\ V}{1\ mV} = 108.922\ k\Omega$

V_{BE} = 0.6 V

	β	r_π	g_m
Measured	166.7	4.167 kΩ	0.040
Datasheet (Mean Values)	175	4.375 kΩ	0.040



Circuit 4:Bias Network for npn transistor

C. **Bias Network**

i. Values of all the currents:

$$I_C = \boldsymbol{1mA}\ ;\ I_B = \frac{I_C}{\beta} = \mathbf{6\mu A};\ \mathrm{I_E} = \mathrm{I_C} + \mathrm{I_B} = \mathbf{1.006mA}$$

Mesh Analysis from V_{CC} to ground, (V_{CE} = 4 V)

$$15 = I_C R_C + V_{CE} + I_E R_E$$

$$15 - 4 = (1mA)R_C + 1.006mA(\frac{1}{2}R_C)$$

$$R_C = 7318.6959\ \Omega$$

$$R_E = 3659.3479\ \Omega$$

Hence, $V_E = R_E I_E = 3.6593\ V$; $V_C = V_E + V_{CE} = 7.6593\ V$; $V_B = V_E + V_{BE} = 4.4593\ V$

To find R_{B1} and R_{B2} , $V_{CC} = V_B + R_{B1} I_1$; $V_B = R_{B2} I_2$, and $I_1 = I_B + I_2$

Choosing $R_{B1} = 1\ M\Omega$; $\mathrm{R_{B2}} = 939.362\ k\Omega$, Since solving Equations is not Linear.

I_C	I_B	I_E	V_C	V_B	V_E
1.009 mA	6.091	1.105 mA	7.61	4.315	3.714

i. Biasing using 1/3 Rule

$$V_B = \frac{1}{3} V_{CC} = 5V;\ V_C = \frac{2}{3} V_{CC} = 10V\ and\ I_1 = \frac{I_E}{\sqrt{\beta}}$$

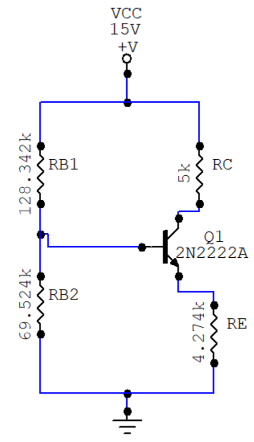
$$V_E = V_B - V_{BE} = 4.4\ V$$

Current Values,

$$I_C = 1mA$$
$$I_B = \frac{I_C}{\beta} = 6\mu\text{A}$$
$$I_E = \text{I}_\text{C} + \text{I}_\text{B} = 1.006 \text{ mA}$$
$$I_2 = I_1 - I_B = \frac{1.006\ mA}{\sqrt{166.7}} - 0.006\ mA = 71.9166\ \mu\text{A}$$

Resistance Values

$$R_C = \frac{V_{CC}}{I_C} = \frac{5V}{1mA} = 5\ k\Omega$$
$$R_E = \frac{V_E}{I_E} = \frac{4.3}{1.006} = 4.274\ k\Omega$$
$$R_{B1} = \frac{V_{CC} - V_B}{I_1} = \frac{10}{77.917} = 128.342\ k\Omega$$
$$R_{B2} = \frac{V_B}{I_2} = \frac{5}{71.92} = 69.524\ k\Omega$$



Circuit 5: 1/3 Rule Bias

DC operating point values (Values are measured in *CircuitMaker*) :

I_C	I_B	I_E	V_C	V_B	V_E
1.024 mA	6.097 µA	1.030 mA	9.889 V	4.996 V	4.395 V

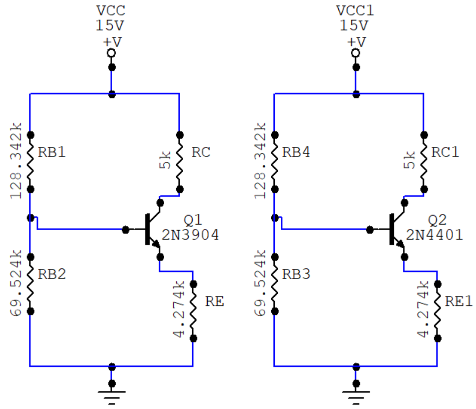
ii. **Using standard Resistor Values**

R_{B1}	R_{B2}	R_C	R_E
130 kΩ	68 kΩ	5.1 kΩ	4.3 kΩ

I_C	I_B	I_E	V_C	V_B	V_E
0.991 mA	5.927 µA	0.997 mA	9.946 V	4.888 V	4.1888 V

iii. On comparison, the values of dc operating points are very similar. But the 1/3 rule is most efficient since it is easy to calculate.

ii. **DC Operating points for 2N3904 and 2N4401**



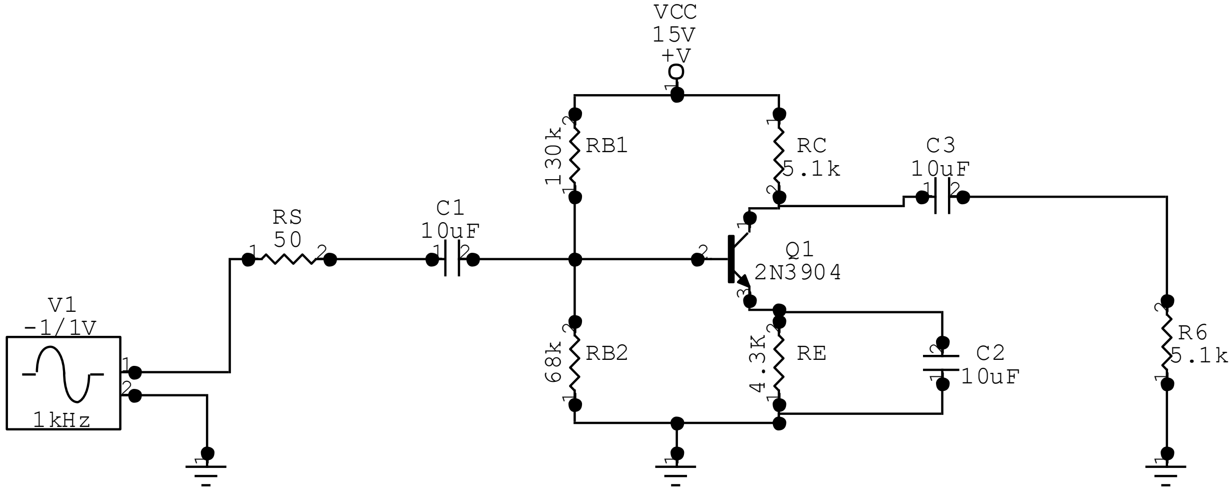
Circuit 6: Bias Circuit for 2N3904 and 2N4401

Using Similar Method and *CircuitMaker* the following values for 2N3904 and 2N4401 are:

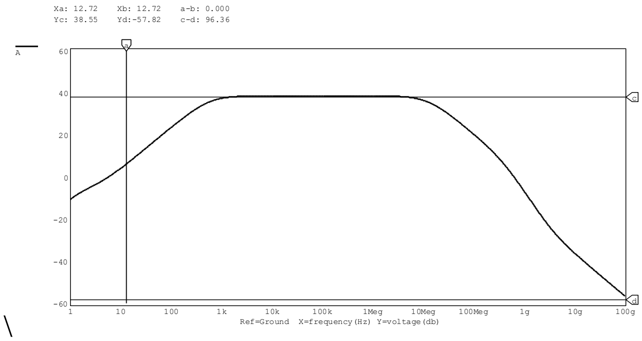
	I_C	**I_B**	**I_E**	**V_C**	**V_B**	**V_E**
2N3904	0.986 mA	8.314 μA	0.994 mA	10.07 V	4.896 V	4.250 V
2N4401	1.003 mA	6.791 μA	1.010 mA	9.995 V	4.965 V	4.307 V
2N2222A	0.991 mA	5.927 μA	0.997 mA	9.946 V	4.888 V	4.1888 V

PART 2

A.

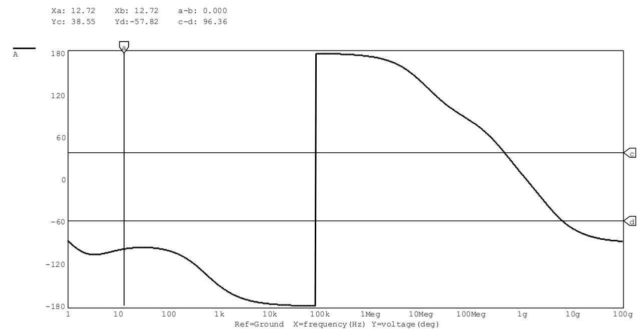


Circuit 7: Common Emitter Amplifier



\

Plot 5:Magnitute Bode Plot



Plot 4:Phase (degrees) Bode Plot

$$g_m = \frac{956.1\mu A}{0.025V} = 0.03824\ S$$

$$V_{CB} = 10.12 - 4.790 = 5.330\ V$$

$$V_{BE} = 4.79 - 4.145 = 0.645\ V$$

$$C_\pi \approx 2 * CJE + TF * g_m = 24.2976\ pF$$

$$C_\mu \approx \frac{CJC}{\left(1 + \frac{V_{CB}}{VJC}\right)^{MJC}} = 1.7545\ pF$$

$$k = -g_m(R_C||R_L) = -102$$

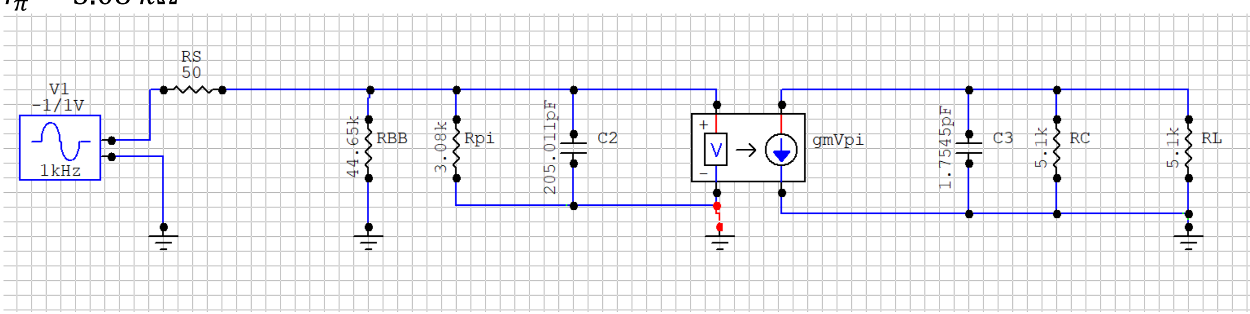
$$r_\pi = 3.08\ k\Omega$$

$$\omega_{LZ3} = \frac{1}{R_E C_E} = 3.7013\ Hz$$

$$\omega_{LP1} = \frac{1}{C_1(R_S + (R_E(1+\beta) + r_\pi)||R_{BB})} = 0.3873\ Hz$$

$$\omega_{LP2} = \frac{1}{(R_L + R_C)C_2} = 1.5603\ Hz$$

$$\omega_{LP3} = \frac{1}{\left(R_E|| \frac{R_{BB}||R_S + r_\pi}{1+\beta}\right) C_1} = 635.278\ Hz$$



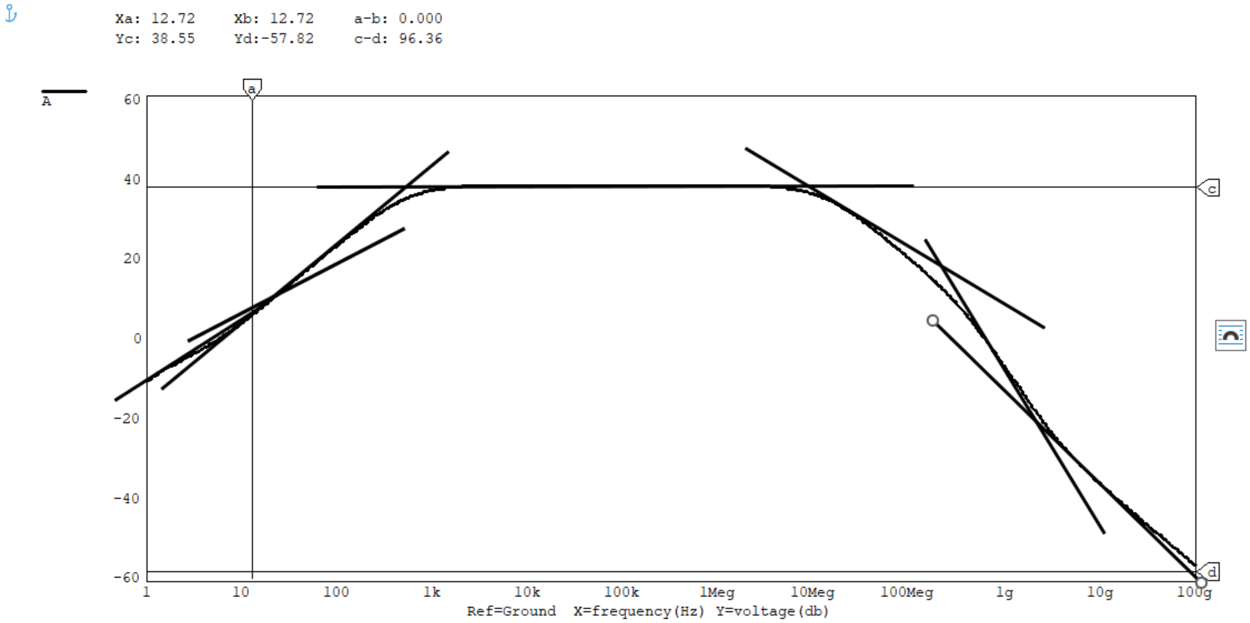
Circuit 8: High frequency small-signal model

$$C_2 = C_\pi + C_\mu(1-k)$$

$$C_3 = C_\mu$$

$$\omega_{HP1} = \frac{1}{(R_{BB}||R_S||r_\pi)C_2} = 15.7959\ MHz$$

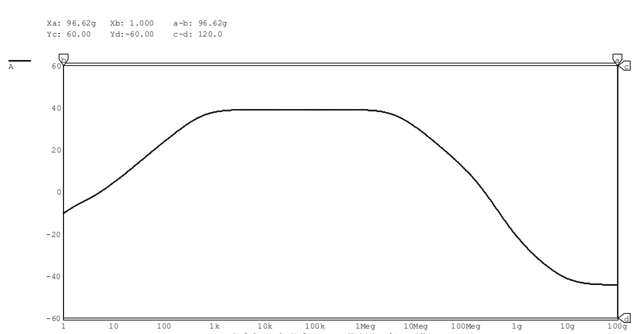
$$\omega_{HP2} = \frac{1}{(R_L||R_C)C_\mu} = 34.3839\ MHz$$



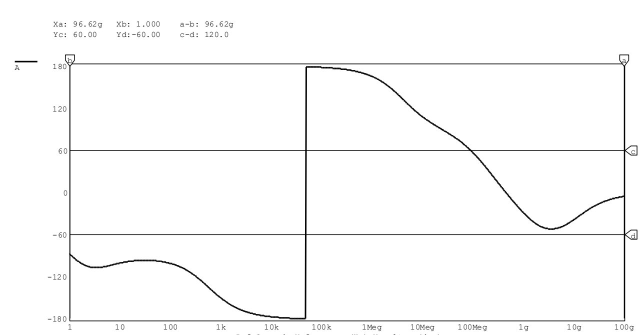
Plot 6: Linear Interpolation for Measuring poles and zeros

	ω_{LZ1}	ω_{LZ2}	ω_{LZ3}	ω_{LP1}	ω_{LP2}	ω_{LL3}	ω_{HP1}	ω_{HP2}
Calculated	0	0	3.701Hz	0.384Hz	1.560Hz	607.75Hz	15.79MHz	34.38MHz
Measured	0	0	4.502Hz	0.557Hz	2.758Hz	690.78Hz	11.67MHz	40.1Mhz

Next, we repeat this process for a 2N4401 transistor, and obtain the poles and zeroes location. by plotting and taking the linear approximation, then by calculations. The same methods are. used as for 2N3904 above.



Plot 8:Magnitude Bode Plot for 2N4401

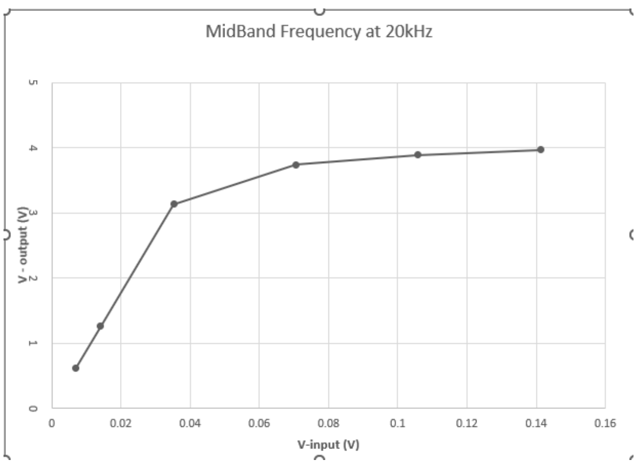


Plot 7: Phase Bode Plot for 2N4401

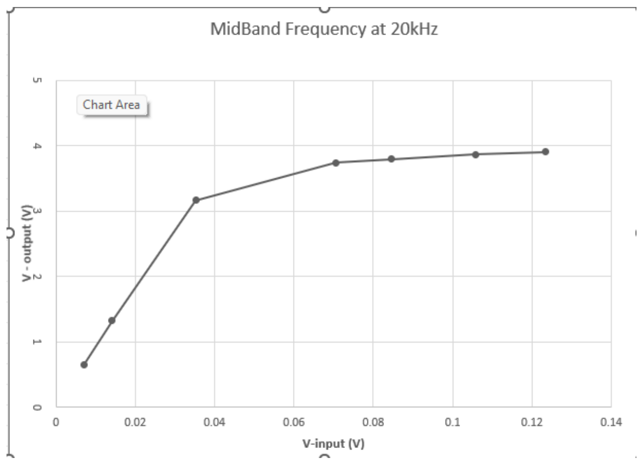
	ω_{LZ1}	ω_{LZ2}	ω_{LZ3}	ω_{LP1}	ω_{LP2}	ω_{LL3}	ω_{HP1}	ω_{HP2}
Calculated	0	0	5.29Hz	0.491Hz	5.81Hz	3.9kHz	105.2MHz	176MHz
Measured	0	0	6.32Hz	0.524Hz	6.69Hz	4.1kHz	112.3MHz	190MHz

B. **Mid Band Frequency**

As we can observe from the Plot 5, the midband frequency ranges from 1kHz to 10Mhz. We choose 20kHz as our midband Frequency to get a non-linear output signal.



Plot 10: Transfer Curve for 2N3904



Plot 9: Transfer Curve for 2N4401

C. **INPUT IMPEDENCE**

Measured Using *CircuitMaker:*

$$\boldsymbol{R_{input} = \frac{V_B}{I_{input}}}$$

2N3904: $Z_{input} = \frac{V_B}{I_{input}} = \frac{4{,}79\ V}{5.36\ mA} = 893.799\ \Omega$

2N4401:$Z_{input} = \frac{4.86V}{5.630mA} = 863.23\ \Omega$

Calculated:

2N3904: $Z_{input} = R_{B1}||R_{B2}||r_\pi = 2.867\ k\Omega$

2N4401:$Z_{input} = 2.395\ k\Omega$

D. **OUTPUT IMPEDENCE**

Measured Using *CircuitMaker:*

$$\boldsymbol{R_{input} = \frac{V_c}{I_{out}}}$$

2N3904: $Z_{input} = \frac{4.080\ V}{1.582\ mA} = 2.58\ k\Omega$
2N4401: $Z_{input} = \frac{4.039V}{1.560\ mA} = 2.59\ k\Omega$

Calculated:

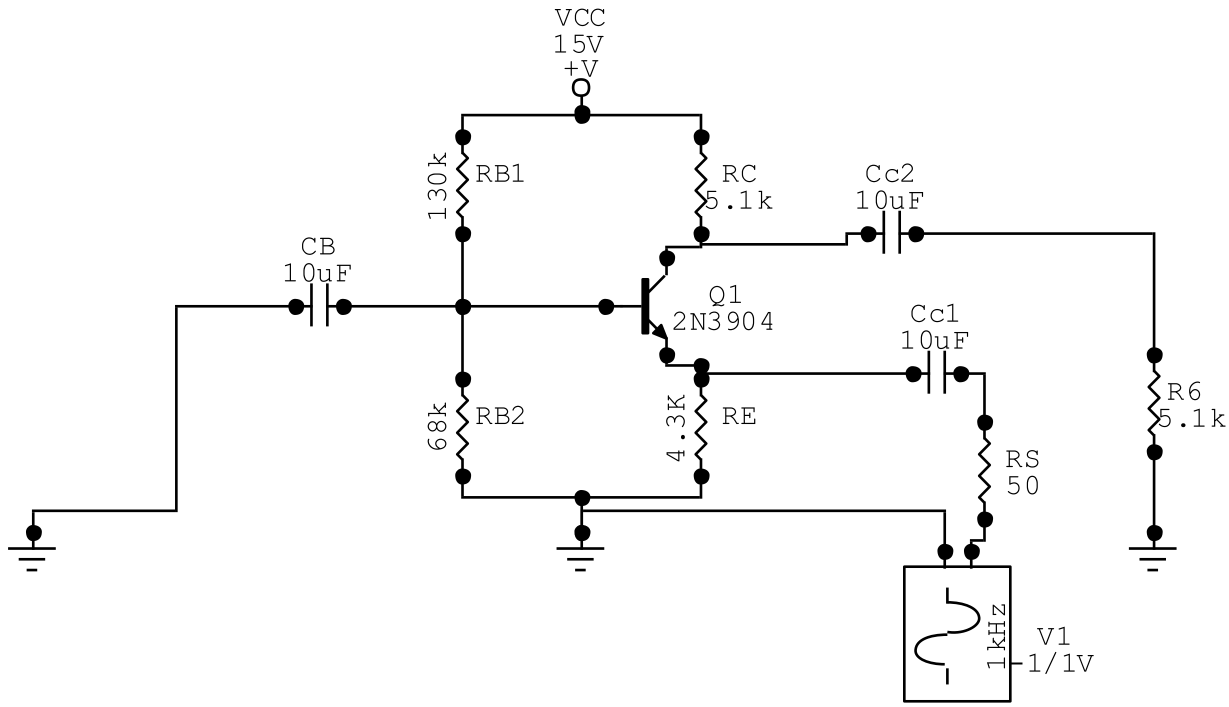
2N3904: $Z_{input} = R_C||R_L = 2.55\ k\Omega$
2N4401: $Z_{input} = 2.55\ k\Omega$

E. **Best Performance Transistor**

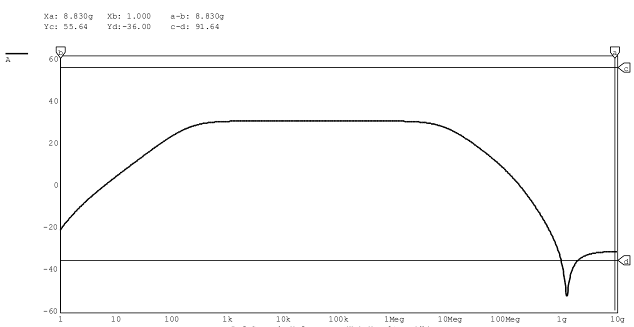
I believe 2N3904 is better as it can handle high currents and gets a linear output domain at much lower peak amplitude as compared to 2N4401.

PART 3

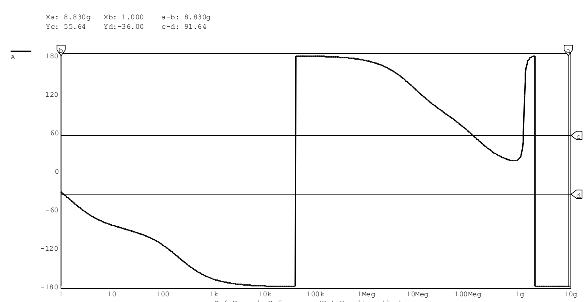
A.



Circuit 9:Common Base Amplifier



Plot 12: Magnitude Bode Plot for CB Amplifier



Plot 11: Phase Bode Plot for CB Amplifier

$$g_m = \frac{993.3\mu A}{0.025V} = 0.039732\ S$$

$$V_{CB} = 5.058\ V$$

$$V_{BE} = 0.601\ V$$

$$C_\pi \approx 2 * CJE + TF * g_m = 74.77360\ pF$$

$$C_\mu \approx \frac{CJC}{\left(1 + \frac{V_{CB}}{VJC}\right)^{MJC}} = 7.73544\ pF$$

$$k = -g_m(R_C||R_L) = -101.316$$

$$r_\pi = 4.17\ k\Omega$$

$$\omega_{LZ3} = \frac{1}{R_{BB}C_B} = 0.357\ Hz$$

$$\omega_{LP2} = \frac{1}{(R_L + R_C)C_{C2}} = 1.5603\ Hz$$

$$\omega_{LP1} = \frac{1}{C_B((R_E(1+\beta) + r_\pi)||R_{BB})} = 0.3781\ Hz$$

$$\omega_{LP3} = \frac{1}{\left(R_E||\frac{r_\pi}{1+\beta} + R_S\right)C_{C1}} = 535.03\ Hz$$

By shorting all the low frequency capacitors,

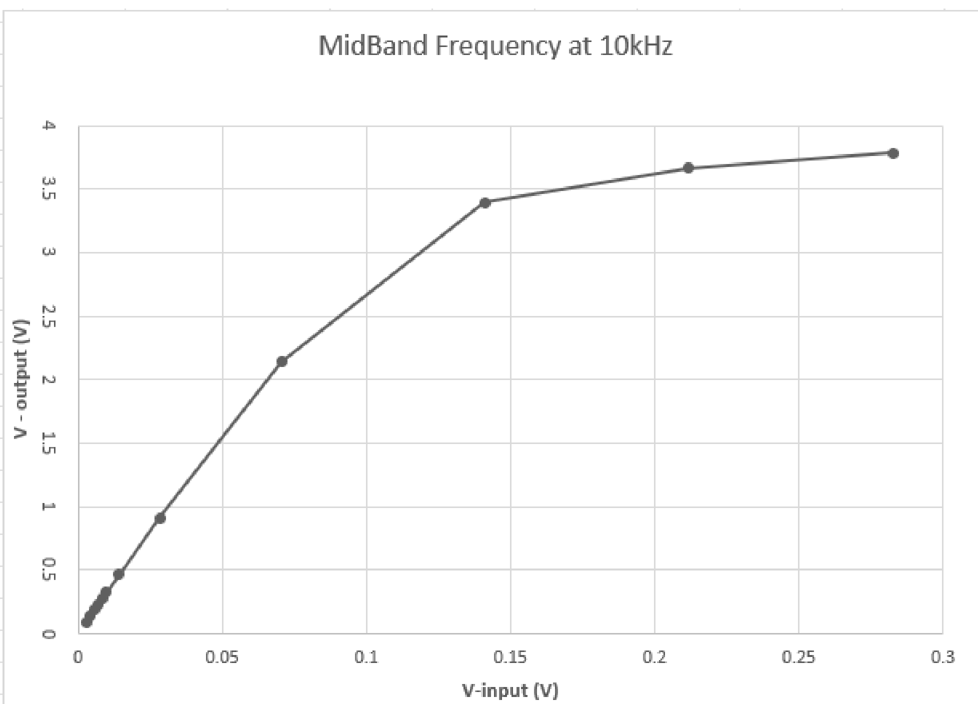
$$\omega_{HP1} = \frac{1}{\left(R_{BB}\middle||R_S C_\pi\middle||\frac{r_\pi}{1+\beta}\right)} = 42.569\ MHz$$

$$\omega_{HP2} = \frac{1}{(R_L||R_C)C_\mu} = 8.06853\ MHz$$

	ω_{LZ1}	ω_{LZ2}	ω_{LZ3}	ω_{LP1}	ω_{LP2}	ω_{LL3}	ω_{HP1}	ω_{HP2}
Calculated	0	0	0.357Hz	0.3781Hz	1.560Hz	535.03Hz	42.569MHz	8.065MHz
Measured	0	0	0.98 Hz	0.42 Hz	3.1 Hz	550.2 Hz	45.76 MHz	9.12 MHz

B. Midband Frequency

From the bode plot, midband frequency ranges from 1kHz to 1MHz. I choose 10kHz to get nonlinear transfer function graph. It is observed that near 70 mV, the output domain starts to get non - linear



Plot 13: Transfer Curve for 2N2222A

C. Input Impedance

Measured: $R_{in} = \frac{V_{in}}{I_{in}} = \frac{704.9\ mV}{5.755\ mA} = 122.48\ \Omega$

Calculated: $R_{in} = R_E || \frac{r_\pi}{1+\beta} = 35.05\ \Omega$

D. Output Impedance

Measured: $R_{out} = \frac{4.002\ V}{1.553 mA} = 2.576\ k\Omega$

Calculated: $R_{out} = R_C || R_L = 2.55\ k\Omega$

Both values are very close.

Conclusion

The goal of this project was to model, bias, and test different types of transistor amplifiers, including Common-base and Common-emitter amplifiers. The first step involved analyzing the characteristics of the transistors at specific voltages and currents, and comparing the results to both calculated values and data from the transistor's datasheet. To ensure that the transistors were operating correctly, they were biased to their DC operating point using a variety of methods, including measurement and the use of the ⅓ rule with standard resistors. The Bode plot was then analyzed to identify the locations of poles and zeroes, and any discrepancies between calculated and measured values were noted. The project also included an investigation into the effects of large signals on small signal models, which provided valuable insight into the performance of the approximate transistor models.

References

1.ELEC 301 Course Notes.

2. 2N2222A Datasheet https://www.st.com/resource/en/datasheet/cd00003223.pdf

3. 2N2222A Datasheet Plots https://web.mit.edu/6.101/www/reference/2N2222A.pdf

4. 2N3904 Datasheet https://www.onsemi.com/pdf/datasheet/2n3903-d.pdf

5. 2N4401 Datasheet https://www.onsemi.com/pdf/datasheet/2n4401-d.pdf