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Table of Contents

Part 1

a) The values of small signal parameters h_{fe} , h_{ie} and h_{oe} for V_{ce} = 10V, I_c = 1 mA, f = 1kHz and T= = 25°C are listed below.

Symbol	**Parameter**	**Minimum Value**	**Maximum Value**
$\mathbf{h_{fe}}$	Small signal current gain	50	300
$\mathbf{h_{ie}}$	Input Impedance	2 kΩ	8 kΩ
$\mathbf{h_{oe}}$	Output admittance	5 µS	35 µS

Table 1.1: Datasheet values for h_{fe}, h_{ie}, h_{oe}

b) i) The circuit used to find I_B vs V_{BE} and the Graph of I_B vs V_{BE} is shown below. The circuit was obtained by performing a DC sweep from 0V to 6V with 0.01V Increments. Doing so, provided us with the following graph.

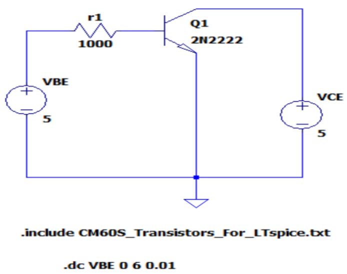

Figure 1: Circuit to find I_B vs V_{BE}

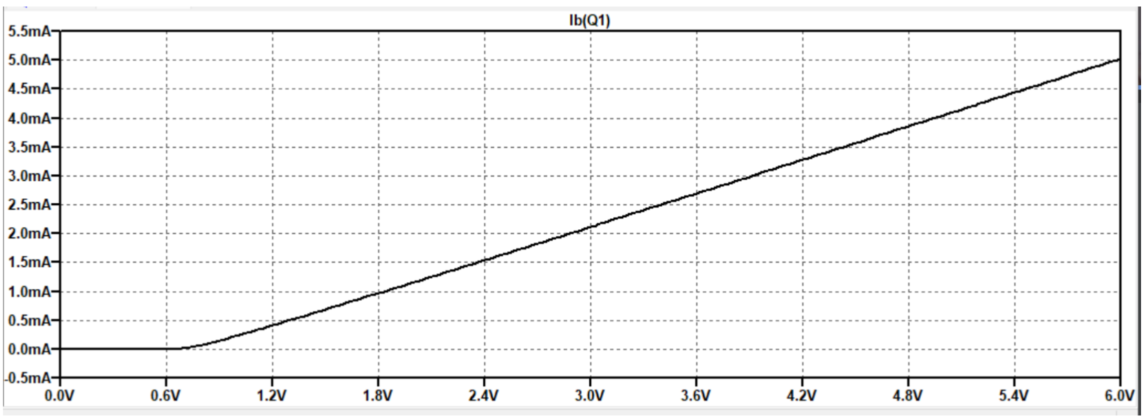

Figure 2: Graph of I_B vs V_{BE}

ii) The circuit used to find I_C vs V_{CE} with varying I_B and the Graph of I_C vs V_{CE} with varying I_B is shown below. The graph was obtained by performing a V_{CE} DC sweep from 0V to 6V with 0.01V increments and an I_B DC sweep from 1µA to 10µA with 1µA increments. Doing so, provided us with the following graphs.

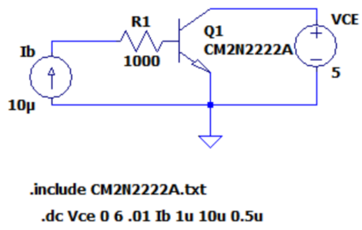

Figure 3: Circuit for finding I_C vs. V_{CE} with varying I_B

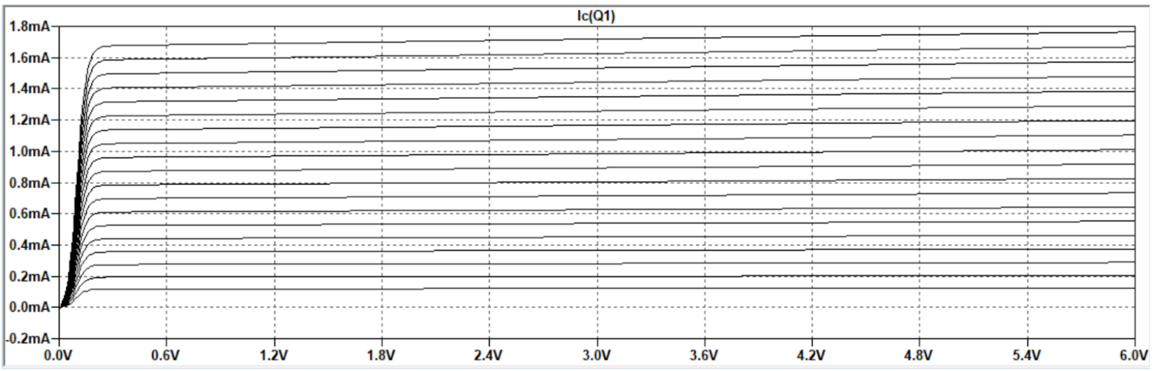

Figure 4: Graph for finding I_C vs. V_{CE} with varying I_B

iii) The circuit used to find I_C vs V_{CE} with V_{BE} as variable parameter and the Graph of I_C vs V_{CE} with V_{BE} as variable parameter is shown below. The graph was obtained by performing a V_{CE} DC sweep from 0V to 6V with 0.01V increments and V_{BE} DC sweep from 0V to 7V with .01 increments. Doing so, provided us with the following graphs.

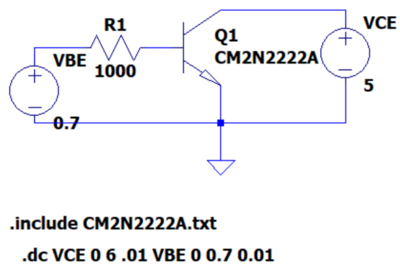

Figure 5: Circuit for I_C vs V_{CE} with V_{BE} as variable parameter

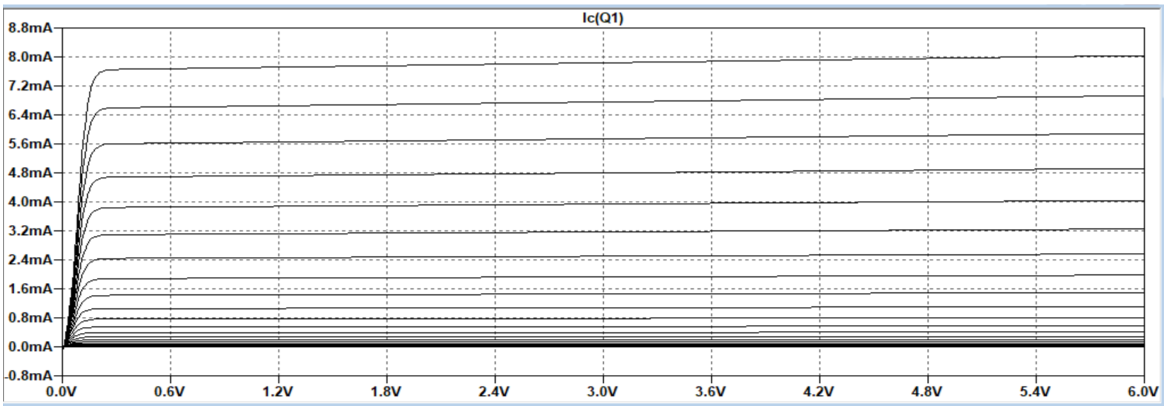

Figure 6: Graph of I_C vs V_{CE} with V_{BE} as variable parameter

Calculating β, r_π, g_m and r_o for V_{CE} = 5V and I_C = 1mA using the plots.

From figure 4, we can find that at V_{CE} = 5v and I_C=1mA, I_B = 6 μA. Thus, we can find the following values of β, r_π and g_m using their relevant equations.

$$\beta = \frac{I_c}{I_B} = \frac{1mA}{6\mu A} = 166.67$$

$$g_m = \frac{I_c}{V_T} = \frac{1mA}{25mV} = 0.04 \mho$$

$$r_\pi = \frac{\beta}{g_m} = \frac{166.67}{0.04} = 4166.75\,\Omega$$

Finding r_o:

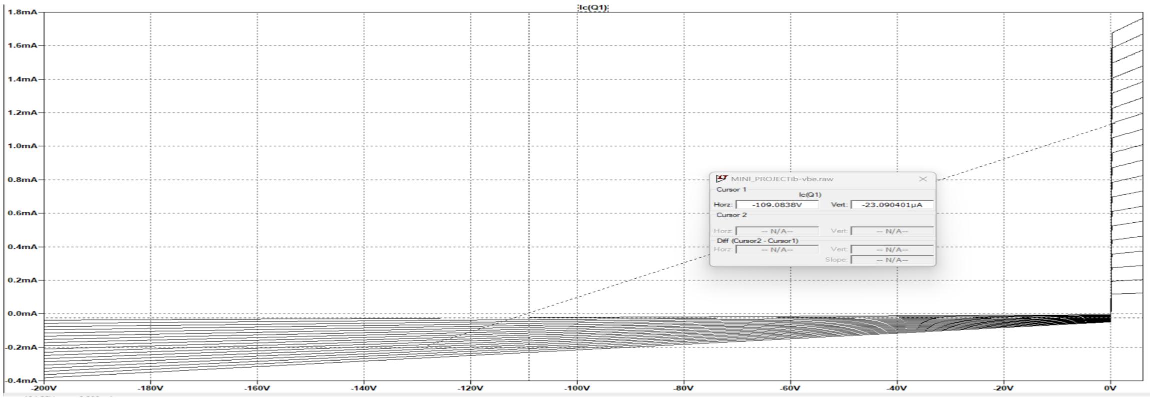

Figure 6: Graph for finding V_A

From the graph, we find V_A to be: 109.0838 V. Thus, the r_o is the following:

$$r_o = \frac{V_A}{I_c} = \frac{109.0838}{1\,mA} = 109.0838\,k\Omega$$

Now we compare these “measured” values with the values from the datasheet.

Symbol	Parameter	Minimum Value	Maximum Value	Calculated Values
h_{fe} / β	Small signal current gain	50	300	166.67
h_{ie} / r_π	Input Impedance	2 kΩ	8 kΩ	4.16675 kΩ
h_{oe} / $1/r_o$	Output admittance	5 µS	35 µS	9.167264 µS

Table 1.2: comparison of "measured" value with the values from datasheet

c) i) For this part of the problem, we are using the "measured" parameters from part b to bias the circuit for a value of V_{CE} of 4V or less and $R_E = R_C/2$ in order to measure the DC operating point From the graph at figure 2, we have found the the value of V_{BE} to be equal to 0.6159 V. We also know the value of β = 166.67 from part B. We are also given that V_{CC} = 15 V and I_C = 1 mA in the question.

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

$$V_{CC} = I_C R_C + V_{CE} + \frac{I_C R_C}{2\alpha}$$

$$R_C = \frac{V_{CC} - V_{CE}}{I_C + \frac{I_C(\beta+1)}{2\beta}}$$

$$R_C = 7318.69623361\ \Omega$$

$$R_E = \frac{R_C}{2}$$

$$R_E = 3659.3481168\ \Omega$$

Now, we analyze the bias circuit and acquire the following two equations.

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

$$\frac{R_{B2}}{R_{B1} + R_{B2}} V_{CC} = I_B \frac{R_{B1} R_{B2}}{R_{B1} + R_{B2}} + V_{BE} + V_E$$

As we can see that the set of equations achieved are not linear. Thus, cannot be solved. Thus, we assume that R_{B1} = 20 kiloohms since we know that the input resistance pf a common emitter amplifier is usually very high. Now that we have a value for R_{B1}, we can use it to find a value for R_{B2}.

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

$$V_E = I_E R_E$$

$$= \frac{I_C R_E (\beta+1)}{\beta}$$

$$= 3.68133037(639 V$$

$$V_{BE} = V_B - V_E$$

$$V_{BE} + V_E = V_B$$

$$0.616 + 3.681330 = V_B$$

$$V_B = 4.2973037 6639$$

$$R_{B2} = 8121.37605955\ \Omega$$

Now, using the resistor values from above, we can find the DC operating point.

Parameter	**I_C**	**I_B**	**I_E**	**V_C**	**V_B**	**V_E**
Values	1.0038 mA	6.0620 µA	1.0099 mA	7.6533 V	4.29694 V	3.69552 V

Table 1.3: DC operating point for when R_{B1} = 20 kΩ and R_{B2} = 8121.37605955 Ω

ii) For this part of the problem, we use the 1 ⁄ 3 rule to bias the circuit in order to find the DC operating point.

$$V_B = \frac{1}{3} V_{cc} = 5V$$

$$V_C = \frac{2}{3} \times V_{cc} = 10V$$

$$V_E = \frac{1}{3} V_{cc} - V_{BE} = 4.3841\ V$$

$$I_C = 1mA$$

$$I_B = \frac{I_C}{\beta} = 5.9999\ \mu A$$

$$I_E = I_C + I_B = 1.0060\ mA$$

$$I_1 = \frac{I_E}{\sqrt{\beta}} = \frac{\frac{I_C}{\alpha}}{\sqrt{\beta}} = \frac{\frac{I_C}{\frac{\beta}{\beta+1}}}{\sqrt{\beta}}$$

$$= 77.9236\ \mu A$$

$$R_C = \frac{V_{cc}}{3 I_C} = 5\ k\Omega$$

$$R_{B1} = \frac{2V_{cc}}{3I_1} = 128.330766661\ k\Omega$$

$$R_{B2} = \frac{V_{cc}}{3(I_1 - I_B)} = 69.5180598255\ k\Omega$$

$$R_E = \frac{V_E}{I_E} = 4.35795280612\ k\Omega$$

Now, using the resistor values from above, we can find the DC operating point.

Parameter	**I_C**	**I_B**	**I_E**	**V_C**	**V_B**	**V_E**
Values	1.0036 mA	5.9833 μA	1.0096 mA	9.9820 V	5.0008 V	4.3997 V

Table 1.4: DC operating point using ⅓ rule

iii) Commonly used resistor values that are closest to the obtained value in ii are listed below. R_C = 5.1 kΩ , R_E = 4.3 kΩ , R_{B1} = 130 kΩ , R_{B2} = 68 kΩ

Parameter	**I_C**	**I_B**	**I_E**	**V_C**	**V_B**	**V_E**
Values	0.9910 mA	5.9120 μA	0.9969 mA	9.9457 V	4.8876 V	4.2869 V

Table 1.5: DC operating point using commonly available resistors

iv) From the table 1.3, 1.4 and 1.5 we can make the following observations:

- The D.C operating point values for part ii) and iii) are notably alike, as one would anticipate, given that iii) derives its values by adopting the calculated values from ii) and aligning them with standard resistors.
- The difference in voltage between i) and ii) can be attributed to the deliberate choices we made when selecting resistor values. This disparity is expected when compared to a systematic approach, as opposed to a more speculative one.

d) Replacing 2N2222A transistor with 2N3904 yields the following DC operating points

Parameter	I_C	I_B	I_E	V_C	V_B	V_E
Values	0.9559 mA	8.0927 μA	0.9640 mA	10.1247 V	4.7902 V	4.1454 V

Table 1.6: DC operating points for 2N3904 using commonly available resistors

e) Replacing 2N2222A transistor with 2N4401 yields the following DC operating points

Parameter	I_C	I_B	I_E	V_C	V_B	V_E
Values	0.9699 mA	6.6194 μA	0.9765 mA	10.0533 V	4.8559 V	4.1992 V

Table 1.7: DC operating points for 2N4401 using commonly available resistors

Discussion:

In this question, we started by extracting small-signal parameters (h_{fe}, h_{ie}, and h_{oe}) from the datasheet for the 2N2222A transistor under specific bias conditions. We then used simulation software such as lt spice to obtain characteristic plots and β, r_π, g_m and r_o for this transistor, comparing our "measured" values with those from the datasheet. Next, we explored different biassing methods for the 2N2222A and compared their DC operating points. Finally, we replaced the 2N2222A with 2N3904 and 2N4401 transistors, comparing their DC operating points. Doing such provided us practical insights into biasing techniques, small-signal parameters, and transistor performance, highlighting the importance of appropriate biasing methods and the impact of different transistor models on circuit behavio

Part 2

a)

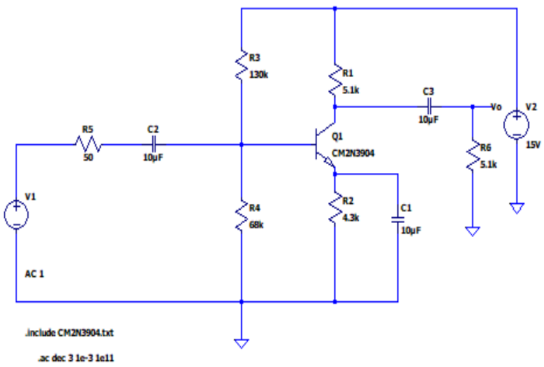

Figure 2.1: Circuit for 2N3904

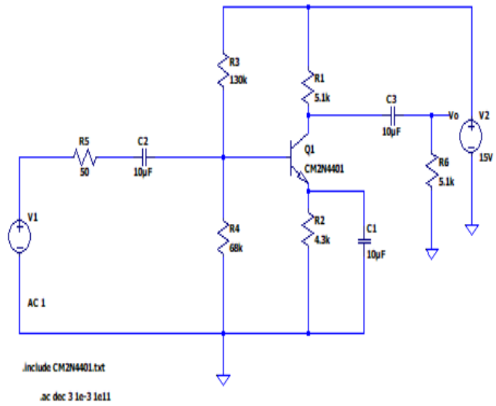

Figure 2.2: Circuit for 2N4401

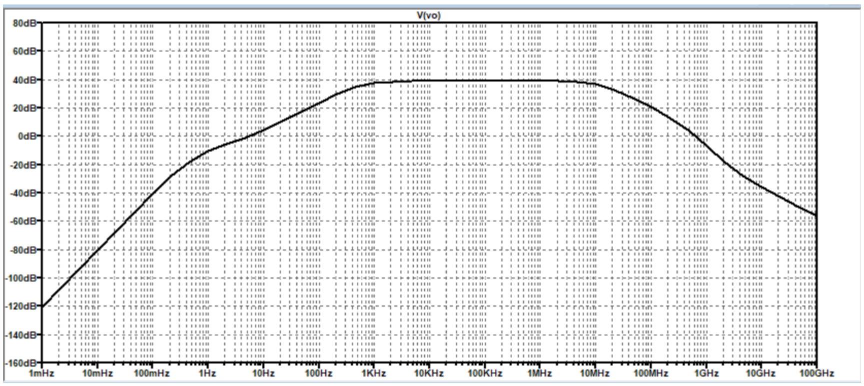

Figure 2.1: Magnitude plot for CM2N3904

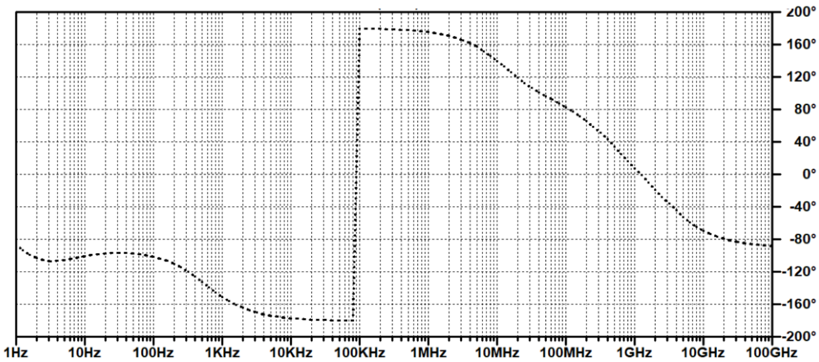

Figure 2.1: Phase plot for CN2N3904

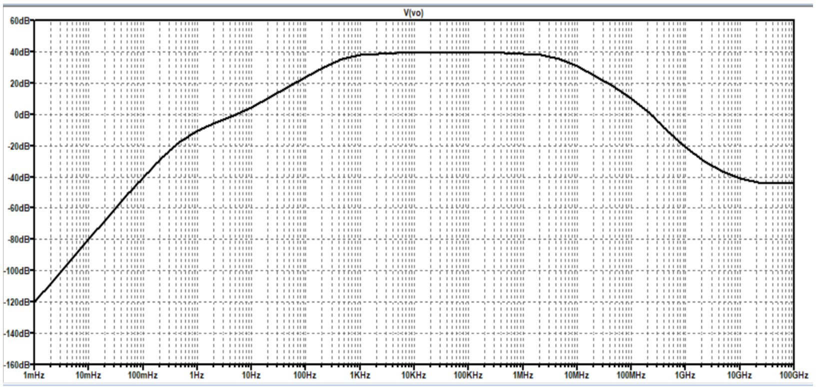

Figure 2.4: Magnitude plot for CM2N4401

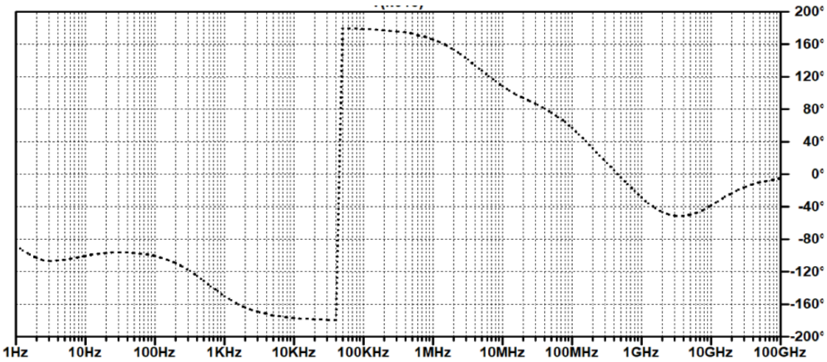

Figure 2.5: Phase plot for CM2N4401

In order to calculate the poles and zeros, we need to acquire the values of β, r_π , C_π , C_μ. The values of I_C , I_B were obtained from table 1.6 and 1.7.

2N3904

$\beta = \frac{I_c}{I_B} = 118.1188$

$r_\pi = \frac{\beta}{g_m} = 3089.2039\ \Omega$

2N4401

$\beta = \frac{I_c}{I_B} = 146.5239$

$r_\pi = \frac{\beta}{g_m} = 3776.7779$

The following values are equations are used to find C_π and C_μ .

$$C_\pi = 2 * CJE + TF * g_m$$

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

Transistor	**VJC**	**MJC**	**CJE**	**TF**	**CJC**
2N3904	0.75	0.33	$4.5*4.510^{-12}$	$400*10^{-12}$	$3.5*10^{-12}$
2N4401	0.75	0.33	$23.4*10^{-12}$	$512*10^{-12}$	$10.2*10^{-12}$

Table 2.1 : Values needed to calculate C_π and C_μ

Equations required to calculate the poles and zeros for the transistors are listed below and the calculated and simulated values for 2N3904 and 2N4401 transistors are listed below.

$$R_{BB} = R_{B1} \| R_{B2} \qquad R_B = R_{BB} \| r_\pi \qquad C = C_\pi + C_\mu\left(1 + g_m\left(R_L \| R_C\right)\right)$$

$$\omega_{LZ1} = \omega_{LZ2} = 0\ rad/s \qquad \omega_{LZ3} = \frac{1}{R_E C_E}$$

$$\omega_{HP1} = \frac{1}{(C)\left(R_S \| R_{BB} \| r_\pi\right)} \qquad \omega_{HP2} = \frac{1}{C_\mu\left(R_L \| R_C\right)}$$

$$\omega_{LP1} = \frac{1}{C_{C1}\left(R_S + R_{BB} \| \left(r_\pi + (1+\beta)R_E\right)\right)} \qquad \omega_{LP2} = \frac{1}{C_{C2}\left(R_C + R_L\right)}$$

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

rad/s	W_{LP1}	W_{LP2}	W_{LP3}	W_{LZ1}	W_{LZ1}	W_{LZ3}	W_{HP1}	W_{HP2}
Simulated 2N3904 values	2.4351 rad/s	9.8004 rad/s	3.9991 krad/s	0 rad/s	0 rad/s	21.2091 rad/s	69.9922 Mrad/s	1.4321 Grad/s
Calculated 2N3904 values	2.4309 rad/s	9.8039 rad/s	3.8801 krad/s	0 rad/s	0 rad/s	23.2551 rad/s	99.9001 Mrad/s	219.4401 Mrad/s
Simulated 2N4401 values	2.4401 rad/s	10.3901 rad/s	3.9091 krad/s	0 rad/s	0 rad/s	29.4021 rad/s	27.1421 Mrad/s	680.4712 Mrad/s
Calculated 2N4401 values	2.3941 rad/s	9.7841 rad/s	3.8891 krad/s	0 rad/s	0 rad/s	23.2565 rad/s	34.4661 Mrad/s	75.2912 Mrad/s

Table 2.2: Simulated and calculated poles and zeros of 2N3904 and 2N4401 transistor

The graphical representation of how to find the simulated poles and zeroes are shown in appendix A.

From the above graph we can see that although the values of low frequencies are fairly close to each other, a greater discrepancy of values are seen at high frequencies. This is due to the fact that Miller's theorem becomes inaccurate at high frequencies and also may be due to the fact that we are ignoring r_o.

b) I have picked the frequency 100kHz from the bode plot. Next, I have used this frequency and adjusted the amplitude of the input amplitude and plotted the V_o vs V_{in} graph in excel in order to obtain the voltage transfer curve.

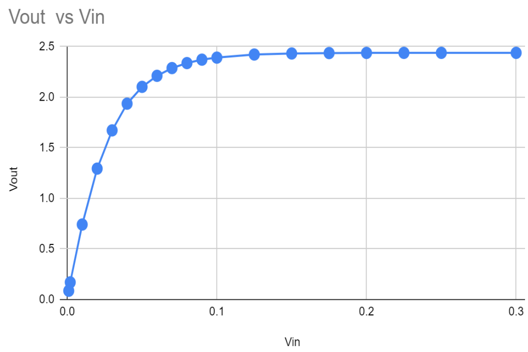

Figure 2.6: Transfer Function plot for 2N3903

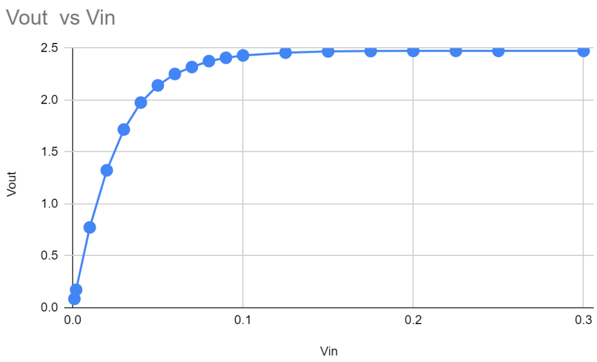

Figure 2.7: Transfer Function plot for 2N4401

As seen from the plots above, the output voltage exhibits non-linearity around 40 mV.

c and d)

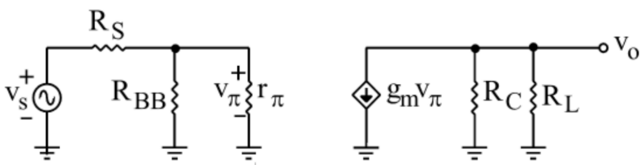

Figure 2.8: the midband circuit

The R_S value is asked to be ignored in the question.

$Z_{in} = R_{BB} \parallel r_{\pi}$, $Z_{out} = R_C$

Transistor	Calculated Values	Simulated Values
2N3904	2889.2867 Ω	3605.9451 Ω
2N4401	3482.2071 Ω	4577.2849 Ω

Figure 2.3: Calculated and simulated Input Impedance for 2N3904 and 2N4401

Transistor	Calculated Values	Simulated Values
2N3904	5100 Ω	2.3042 Ω
2N4401	5100 Ω	2.4932 Ω

Figure 2.4: Calculated and simulated output Impedance for 2N3904 and 2N4401

e) In order to understand which transistor would be a better choice I have analysed the discrepancy between simulated and calculated of high frequency poles. Upon analysing, I have noticed that the difference of high frequency pole in 2N4401 is much smaller than 2N3904. Thus, 2N4401 is a better choice.

Discussion:

For the above part of our project, we established a common Emitter amplifier using a 2N3904 transistor and performed various analyses. We began by plotting Bode magnitude and phase diagrams to identify pole and zero locations and compared our estimates with calculated values, repeating the process for the 2N4401 transistor. We then adjusted the input signal's amplitude to detect non-linear behaviour in the output for both transistors, helping us understand their linearity limits. Additionally, we measured and compared the input and output impedances of the amplifiers with theoretical calculations for both transistors. Based on these findings, we selected the transistor that offered the best performance.

<u>Part 3:</u>

a)

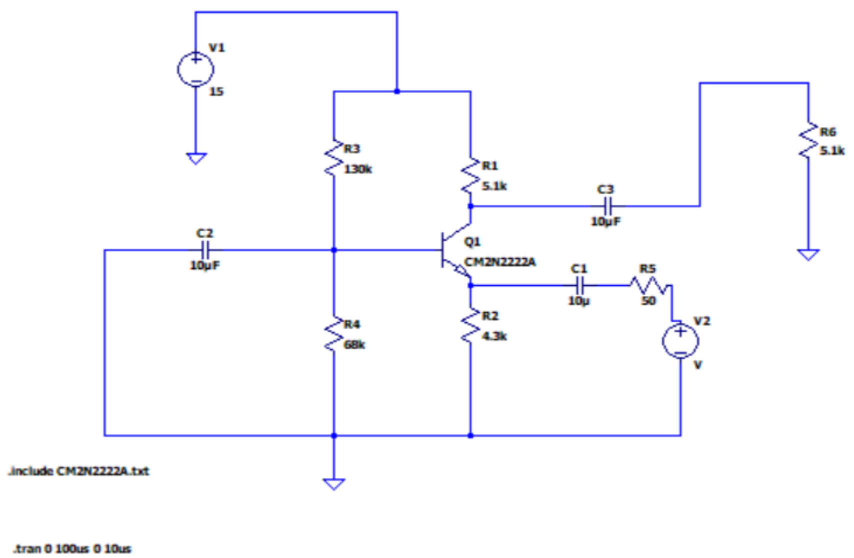

Figure 3.1: Simulated Circuit for 2N2222A Plots

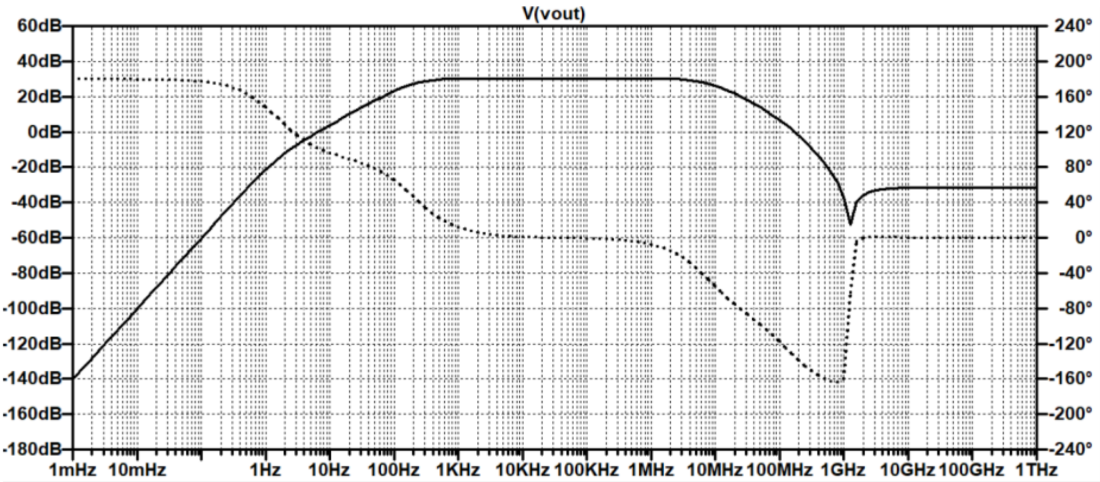

Figure 3.2: Bode and Phase Plot for 2N2222A

From part 1, we have acquired the following values for β, r_π and g_m.

$$\beta = \frac{I_C}{I_B} = \frac{1mA}{6\mu A} = 166.67$$

$$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = 0.04 \mho$$

$$r_\pi = \frac{\beta}{g_m} = \frac{166.67}{0.04} = 4166.75\ \Omega$$

In order to calculate the poles, we also would require the value of C_π and C_μ.

$$C_\pi = (2)(CJE) + (TF)(g_m) = 74.88\ pF$$

$$C_\mu = \frac{CJC}{\left(1 + \frac{VCB}{VJC}\right)^{MJC}} = 7.74\ pF$$

Now, we use the following equations from [1] to calculate the values of the poles.

$$W_{LZ1} = 0 \ , \ W_{LZ2} = 0 \ , \ W_{LZ3} = \frac{1}{C_B R_{BB}}$$

$$W_{HP1} = \frac{1}{(R_C \| R_L)(C_\mu)} \ , \ W_{HP2} = \frac{1}{\left(\frac{r_\pi}{1+\beta} \| R_E \| R_S\right)(C_\pi)}$$

$$W_{LP1} = \frac{1}{\left(R_{BB} \| (r_\pi + (1+\beta)R_E\right) C_B} \qquad W_{LP2} = \frac{1}{(R_C + R_L)(C_{C2})}$$

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

Using the equations and the values for poles and zero are calculated and compared with the simulated values for poles and zeros.

	W_{LZ1}	W_{LZ2}	W_{LZ3}	W_{HP1}	W_{HP2}	W_{LP1}	W_{LP2}	W_{LP3}
Calculated	0 rad/s	0 rad/s	2.2398 rad/s	50.6663 Mrad/s	807.1057 Mrad/s	2.3777 rad/s	9.8039 rad/s	1.3629 rad/s
Simulated	0 rad/s	0 rad/s	Not applicable	73.5651 rad/s	1.3851 Grad/s	Not applicable	11.0082 rad/s	1.3871 rad/s

Table 3.1: calculated and measured value for 2N2222A

The graphical representation of how to find the simulated poles and zeroes are shown in appendix B.

b) The steps to complete this part are identical to part 2b. Thus, the chosen frequency is 100kHz for the same reason.

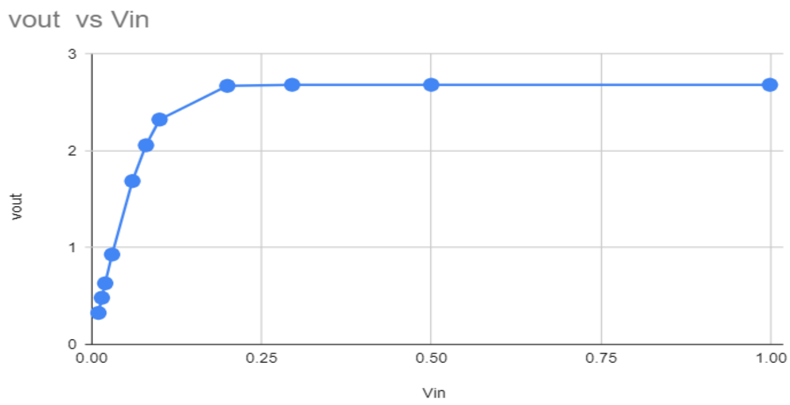

Figure 3.3: Transfer function plot for 2N2222A

As seen from the plots above, the output voltage exhibits non-linearity around 60 mV.

C and d) The equation to calculate input and output impedances are listed below.

$Z_{in} = R_E || \frac{1}{1+\beta} * r_\pi$, $Z_{out} = R_C$

Calculated Values for Z_{in}	Simulated Values for Z_{in}	Calculated Values for Z_{out}	Simulated Values for Z_{out}
24.7081 Ω	26.9877 Ω	5100 Ω	5100.0001 Ω

Table 3.2: calculated and simulated values for input and output impedance

Appendix A:

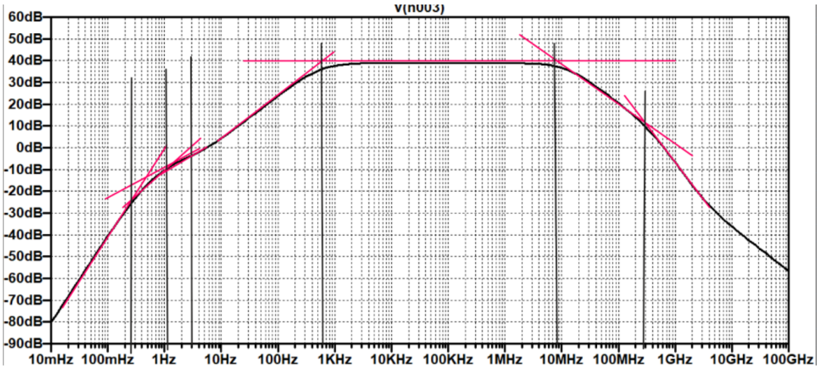

Figure A.1: graphically determining the location of poles and zeroes for CM2N3904

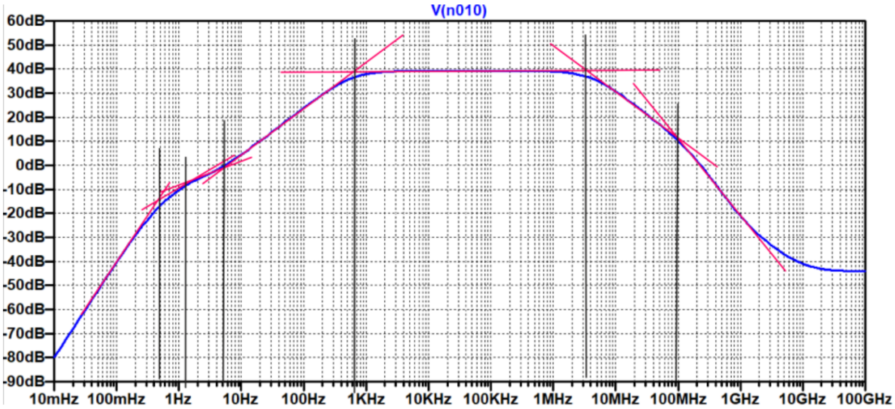

Figure A.2: graphically determining the location of poles and zeroes for CM2N4401

Appendix B:

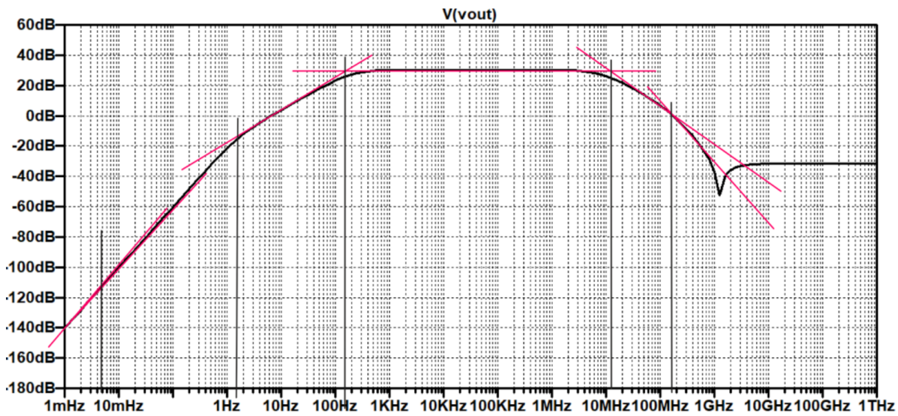

Figure B.1: graphically determining the location of poles and zeroes for CM2N2222A

Reference:

[1] ELEC 301 Course Notes.

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

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