ELEC 301 MINI PROJECT 2

Yi-Chen Lin - 48861785

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1. Objective

Familiarise yourself with the hybrid-π model of transistors and issues related to transistor biassing, as well as analyse and measure the characteristics of an important transistor amplifier. Analyse and measure the characteristics of an important transistor amplifier using 3 common transistors.

2. Introduction

Examines two fundamental single-transistor amplifier circuits: the common emitter and common base amplifiers, utilising the hybrid-π model for small signal operation. The transistors considered for the designs are the 2N2222A, 2N3904, and 2N4401. The focus is on analysing the amplifiers within the transistor's active region, where the hybrid-π model accurately describes the circuit behaviour. If large signals are introduced, the transistor may enter saturation or cut-off modes, rendering the model ineffective for circuit analysis.

3. Project-Questions

3.1 Part 1

3.1 A

Values of the small signal parameter h_{fe}, h_{ie}, h_{oe} for $V_{CE} = 10V,\ I_C = 1mA,\ f = 1KHz$ and $T = 25^oC$

Parameter	Description	Min-Value	Max-Value
h_{fe}	DC Current Gain	50	300
h_{ie}	Input Impedance	2 kΩ	8 kΩ
h_{oe}	Output Admittance	5 µS	35 µS

3.1 B

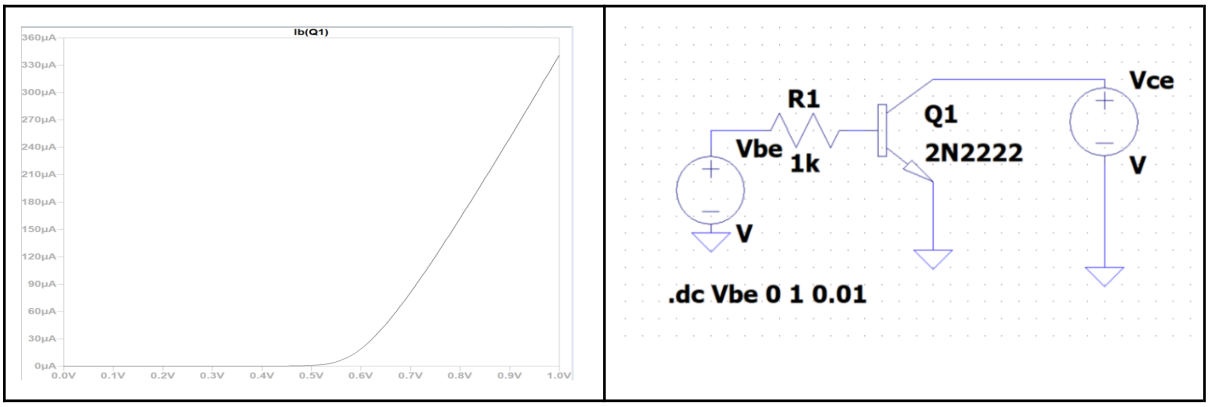


Figure 3.1.1 I_B vs V_{BE} *with varying* I_B

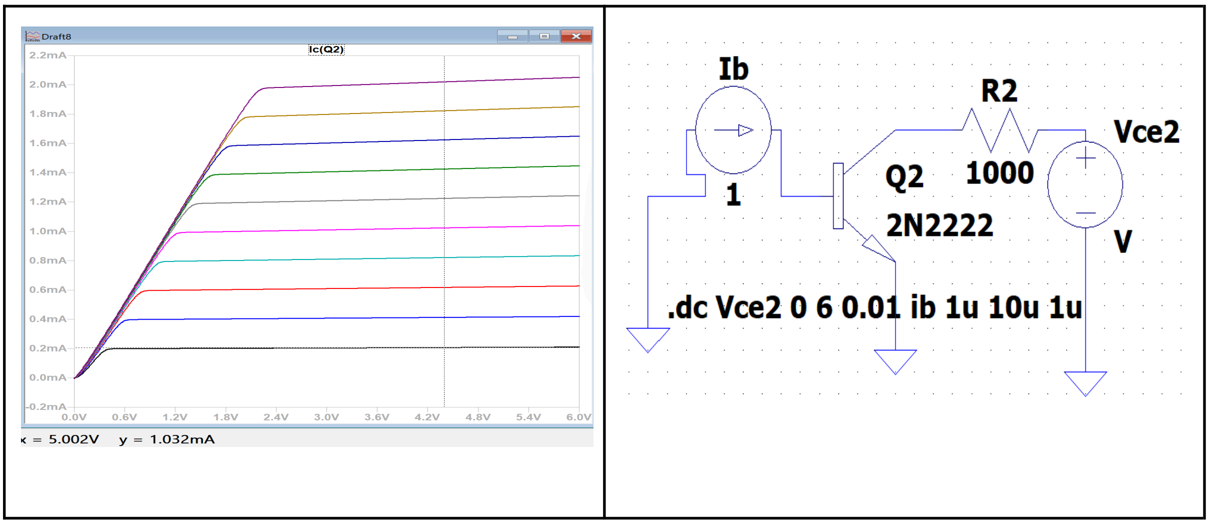


Figure 3.1.2 I_C *vs* V_{CE} *with varying* I_B

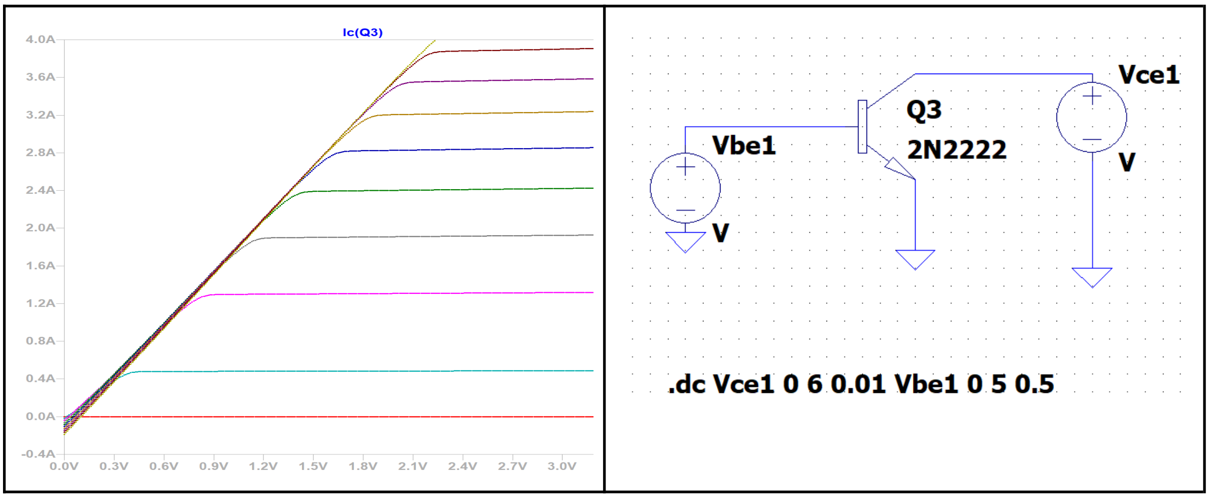


Figure 3.1.3 I_C *vs* V_{CE} *with varying* V_{BE}

With simulation and the set values of $V_{CE} = 5V$ and $I_C = 1\ mA$, we can solve the following

β calculate using Figure 3.1.2,

$$\beta = \frac{I_C}{I_B} = \frac{1.032*1e-3}{5*1e-6} = 206.4$$

Next, r_π can be found by

$$r_\pi = \frac{\beta}{g_m} = \frac{\beta}{\frac{I_c}{V_T}} = \frac{206.4*25mV}{1mA} = 5160\Omega$$

And $g_m = \frac{I_c}{V_T} = 0.04S$

Finally r_o can be commute by $r_o = \frac{V_A}{I_c}$ and for V_A we estimate the slope in the active (saturation) region of the Figure 3.1.3 and solve for the intersection while $I_C = 0$, $V_A =$ -105V and leads to $r_o = \frac{V_A}{I_C} = \frac{105V}{1mA} = 105K\Omega$

After the calculation and measurements, comparing them with the standard value found in 3.1A, all the variables are acceptable in range.

3.1 C

3.1.C.1 Using Given Values with Vcc = 15V, Ic = 1 mA, Vce = 4V and $R_E = \frac{R_c}{2}$

For the current calculation

$$I_B = \frac{1}{\beta} * I_C = 4.84\mu A \text{ and } I_E = I_B + I_C = 1.00484\, mA$$

For Re and Rc calculation

$$15 = I_C * R_C + 4 + I_E * R_E$$

$$15 = I_C * R_C + 4 + I_E * \frac{R_C}{2}$$

We then solved and get $R_C = 7321.509$ and $R_E = 3660.755$

For voltage calculation

$$V_E = I_E * R_E = 3.678V$$

$$V_C = V_E + V_{CE} = 7.678V$$

$$V_B = V_E + V_{BE} = 4.378V$$

Now we can calculate the left Rb resistors with the listed two equation

$$\frac{V_{CC}-V_B}{R_{B1}} - I_B = \frac{V_B}{R_{B2}} \text{ and } V_{CC}[\frac{R_{B2}}{R_{B2}+R_{B1}}] = V_B + I_B * (R_{B1}||R_{B2})$$

And by setting our R_{B1} as $1M\Omega$, it leads to $R_{B2} = 757977\Omega$

Using the upon resistor values, the DC operating point of bias circuit is

I_C	I_B	I_E	V_C	V_B	V_E
1.000 mA	4.892 μA	1.000 mA	7.627 V	4.358V	3.704V

3.1.C.2 Using 1/3rd Rule with Vcc = 15V and Ic = 1 mA

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

And known, $V_{BE} = 0.7, \beta = 206.4$

$$V_E = V_B - 0.7 = 4.3V$$

$$I_B = \frac{1}{\beta} * I_C = 4.84\mu A \text{ and } I_E = I_B + I_C = 1.00484\, mA$$

$$I_1 = \frac{I_E}{\sqrt{\beta}} = 69.606\mu A \text{ and } I_2 = I_1 - I_B = 64.761\mu A$$

After all the current found, we look at the resistor value

$$R_C = \frac{V_{CC}-V_C}{I_C} = \frac{1}{3} * \frac{V_{CC}}{I_C} = 5000\Omega$$

$$R_{B1} = \frac{V_{CC}-V_B}{I_1} = \frac{2}{3} * \frac{V_{CC}}{I_1} = 143.666K\Omega$$

$$R_{B2} = \frac{V_B}{I_2} = 77.207\ k\Omega$$

$$R_E = \frac{V_E}{I_E} = 4279.267\Omega$$

Finally the DC operating point for 1/3rd Rule bias circuit is listed below

I_C	I_B	I_E	V_C	V_B	V_E
1.001 mA	1.356 µA	1.016 mA	9.944 V	5.003V	4.348V

3.1.C.3 Using Standard Resistor Values with Vcc = 15V and Ic = 1 mA

By replacing all the resistor values by the standard resistor value table. We ends up with the following values.

I_C	I_B	I_E	V_C	V_B	V_E
0.953 mA	1.382 µA	0.958 mA	10.013 V	4.773 V	4.120 V

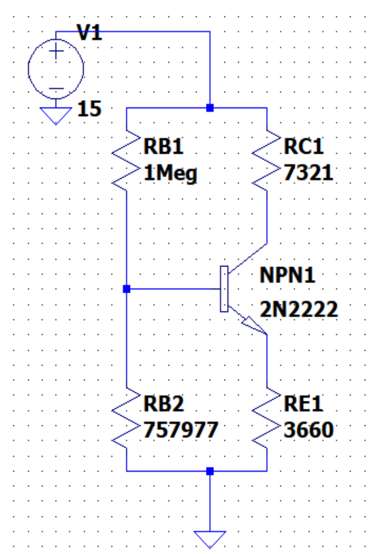


Figure *3.1.C.1 Given Value*

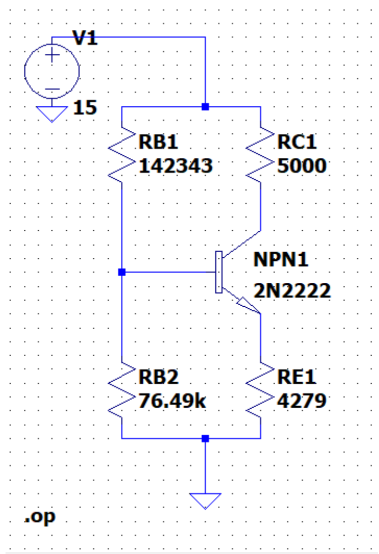


Figure *3.1.C.2 1/3rd Rule*

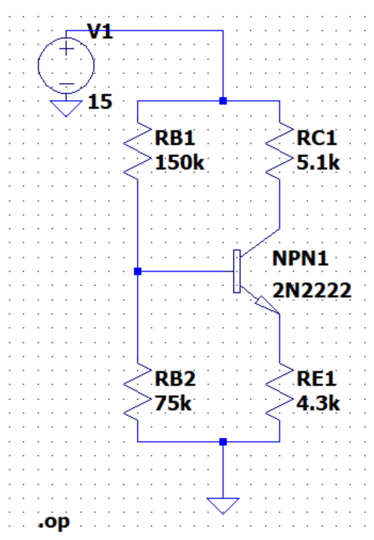


Figure *3.1.C.3 Standard Resistor*

3.1 D

	I_C	I_B	I_E	V_C	V_B	V_E
2N2222	1.001 mA	1.356 μA	1.016 mA	9.944 V	5.003 V	4.348 V
2N3904	1.031 mA	8.811 μA	1.034 mA	9.846V	5.079 V	4.424 V
2N4401	0.976 mA	8.109 μA	0.984 mA	10.120 V	4.840 V	4.211V

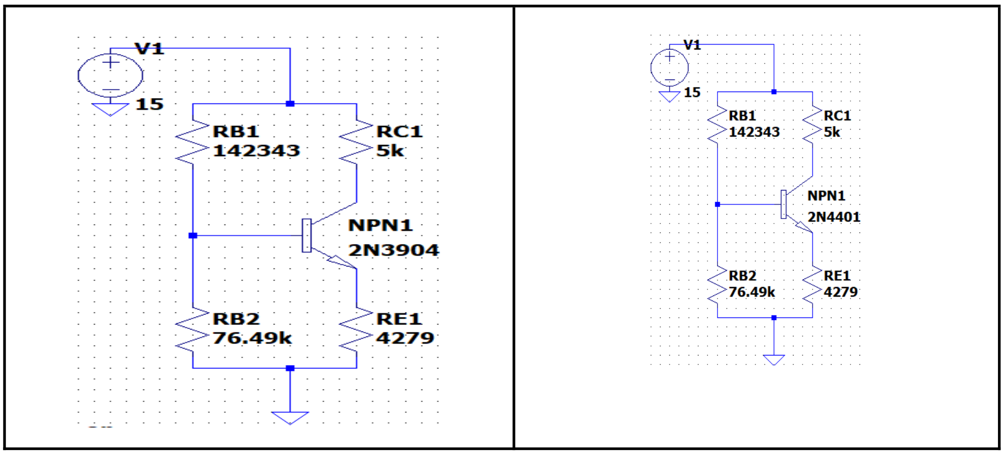


Figure *3.1.D different transistor with ⅓ Rule Circuit*

3.1 Conclusion

All methods provide an adequate bias circuit, but the one-third rule stands out as the most versatile in terms of component selection. It also allows for quicker resistance calculations while still delivering a reliable circuit.

The 2N2222A and 2N4401 have similar operating points, but for the 2N3904, I_B is much higher and V_B is lower than in the others, while all other parameters remain nearly the same.

3.2 Part 2

3.2 A

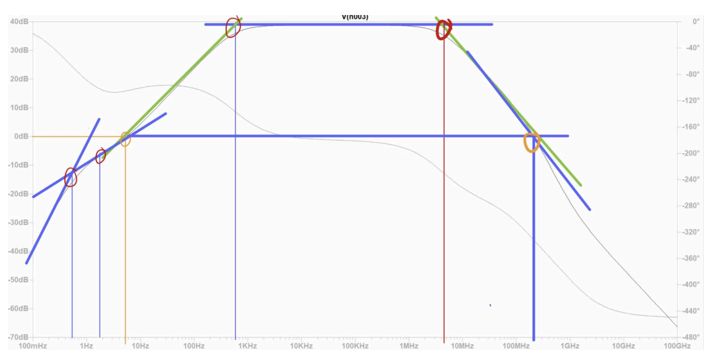
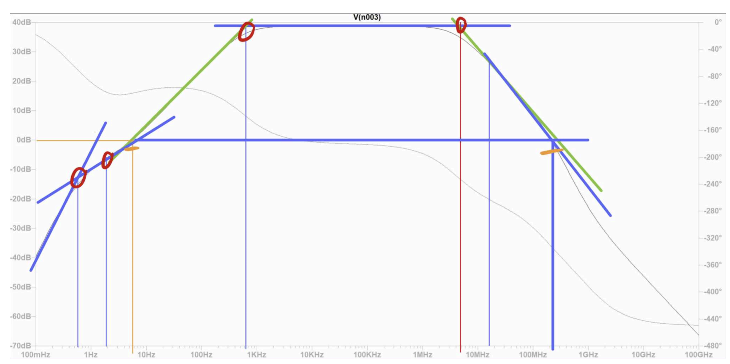
2N4401	2N3904
	

Figure 3.2.1A Bode Plot and Phase Diagram

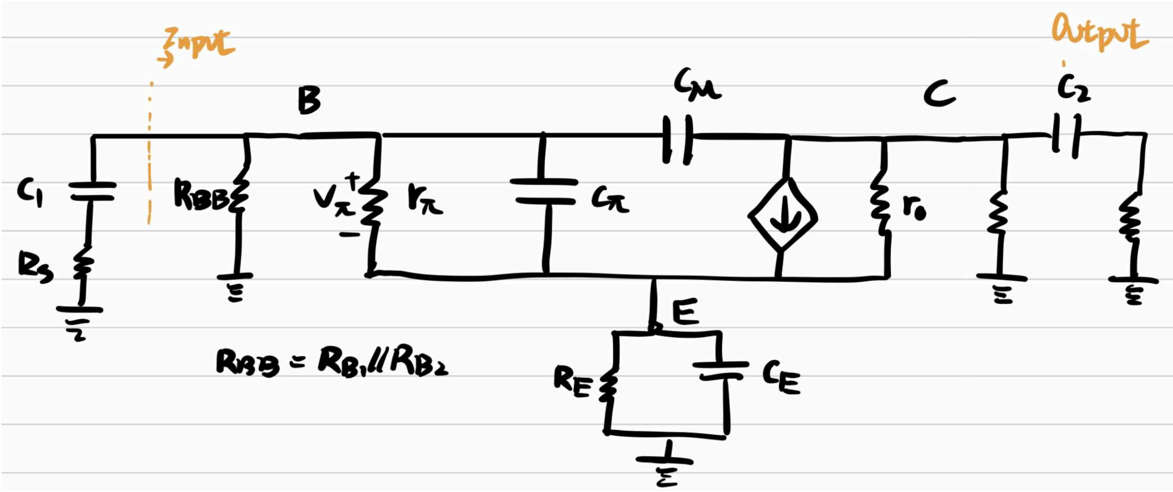


Figure 3.2.1 Complete Small-Signal Model

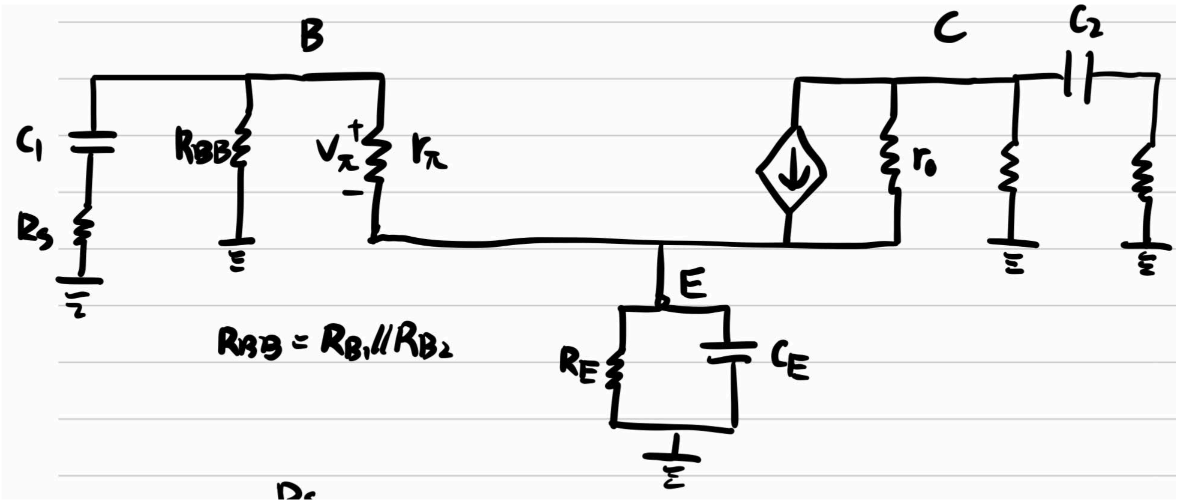


Figure 3.2.2 Low Frequency Model

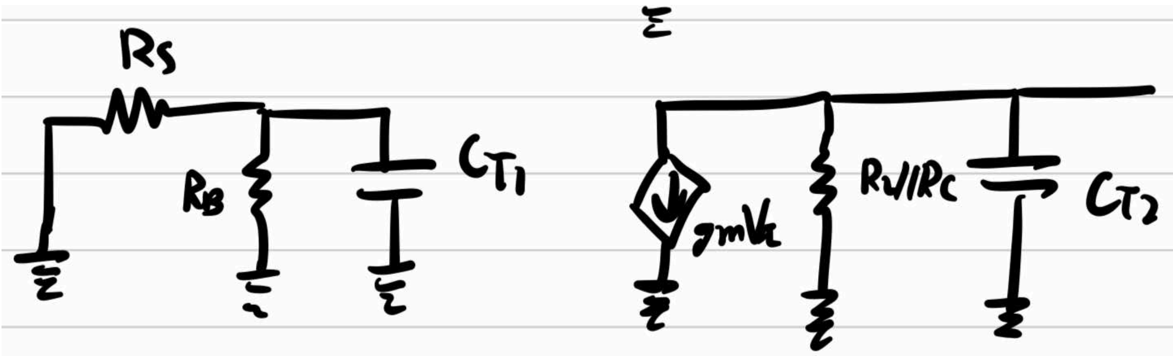


Figure 3.2.3 High Frequency Model

$$C_\pi \approx 2 * CJE + TF * gm \quad \text{and } C_\mu \approx \frac{CJC}{(1+\frac{V_{CB}}{VJC})^{MJC}}$$

From the LTspice, we found the value of C_π and C_μ used the given value.

2N4401 -> $C_\pi \approx 20pF$ and $C_\mu \approx 4.6pF$, $\beta = 120$, $R_\pi = 2.940k\Omega$

2N3904 -> $C_\pi \approx 20pF$ and $C_\mu \approx 4.5pF,\ \beta = 117,\ R_\pi = 2.925k\Omega$

For zero calculation, two connected to the coupling capacitors thus resulting in a 0. And the last zero can be found by

$$\omega_{Lz3} = \frac{1}{R_E * C_R}$$

For the low frequency poles, using the Figure 3.2.2, we generated the following equations

$$\text{OCTC} \rightarrow \omega^{C_1}_{Lp1} = \frac{1}{(R_S + R_{BB} || (R_\pi + (1+\beta) * R_E)) * C_1}$$

$$\text{SCTC} \rightarrow \omega^{C_E}_{Lp2} = \frac{1}{(R_E || \frac{R_\pi + R_S || R_{BB}}{1+\beta}) * C_E}$$

$$\text{SCTC} \rightarrow \omega^{C_2}_{Lp3} = \frac{1}{(R_L + R_C) * C_2}$$

For the high frequency poles, using the Figure 3.2.3, we generated the rest equations

$$\omega^{C_{T1}}_{Hp1} = \frac{1}{(R_S || R_{BB} || R_\pi) * C_{T1})}$$

$$\omega^{C_{T2}}_{Hp2} = \frac{1}{(R_C || R_L) * C_{T2}}$$

Where

$$C_{T1} = (C_\pi + C_\mu (1 + gm * R_C || R_L)$$

$$C_{T2} = C_\mu (\frac{-gm * R_C || R_L - 1}{-gm * R_C || R_L})$$

2N3904	ω_{Lz1}	ω_{Lz2}	ω_{Lz3}	ω_{Lp1}	ω_{Lp2}	ω_{Lp3}	ω_{Hz1}	ω_{Hz2}	ω_{Hp1}	ω_{Hp2}
$\omega_{calculate}$	0	0	23.256	2.193	3989.71	9.804	-	-	42.11M	86.30M
$f_{calculate}$	0	0	3.701	0.349	634.98	1.560	-	-	6.702M	13.73M
$f_{simulate}$	-	-	5.418	0.361	603	1.67	∞	∞	6.9M	191.3M

2N4401	ω_{Lz1}	ω_{Lz2}	ω_{Lz3}	ω_{Lp1}	ω_{Lp2}	ω_{Lp3}	ω_{Hz1}	ω_{Hz2}	ω_{Hp1}	ω_{Hp2}
$\omega_{calculate}$	0	0	23.256	2.153	3798.81	9.804	-	-	41.42M	84.42M
$f_{calculate}$	0	0	3.701	0.342	604.6	1.560	-	-	6.59 M	13.43M
$f_{simulate}$	-	-	5.611	0.346	622.508	1.77	∞	∞	5.152M	200M

3.2 B

By redrawing our small signal model and consider the mid-band, we ends up with circuit

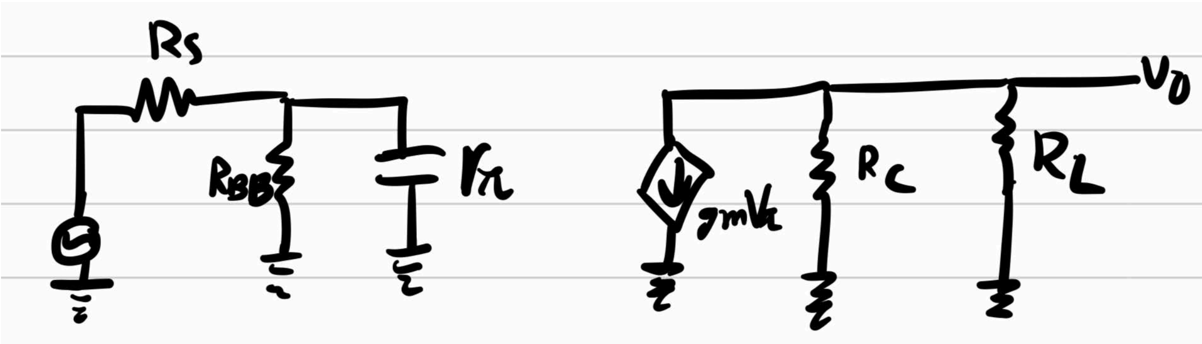


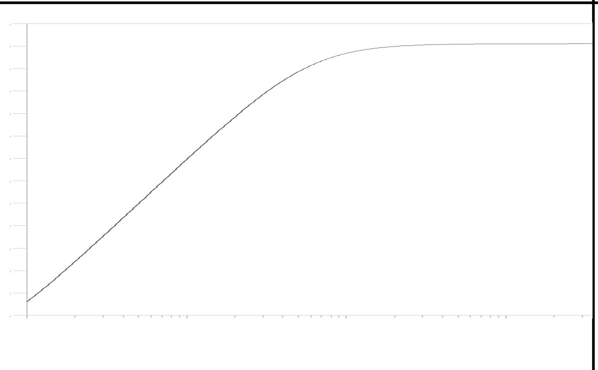
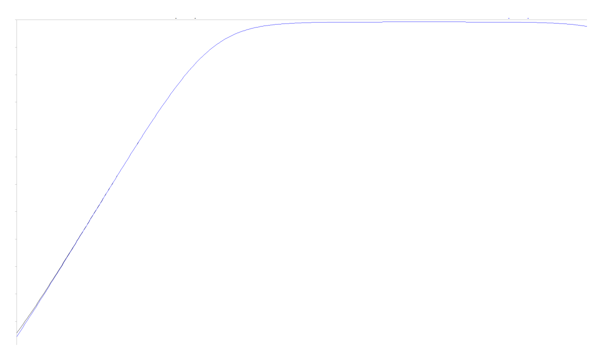
Figure 3.2.4 Mid-Band Model

From the image, we can easily find that

$$A_M = - gm * (R_C || R_L) * \frac{R_{BB} || R_\pi}{R_{BB} || R_\pi + R_S}$$

And after running the simulation for 2 transistors, we ends up with the following results

	2N3904	2N4401
Calculated	-100.187	-100.195
Simulated	-102.251	-101.242

2N3904 - Midband	2N4401 - Midband
	

3.2 C

Input Impedance calculation $R_{in} = R_{BB} || R_\pi$

And by running the simulator, and using formula we get $R_{in} = \frac{V_B}{I_{in}}$

	2N3904	2N4401
Calculated	2763Ω	2776.7Ω
Simulated	2930Ω	3020Ω

3.2 D

Output Impedance calculation $R_{out} \approx R_C$

And by running the simulator, and using formula we get $R_{out} = \frac{V_{out}}{I_{out}}$

	2N3904	2N4401
Calculated	5.1kΩ	5.1kΩ
Simulated	5.1kΩ	5.1kΩ

3.2 E

In this circuit situation, I would choose 2N3904 over 2N4401 as the better performance due to the lower current performance which better matches with our current case.

3.2 Part 3

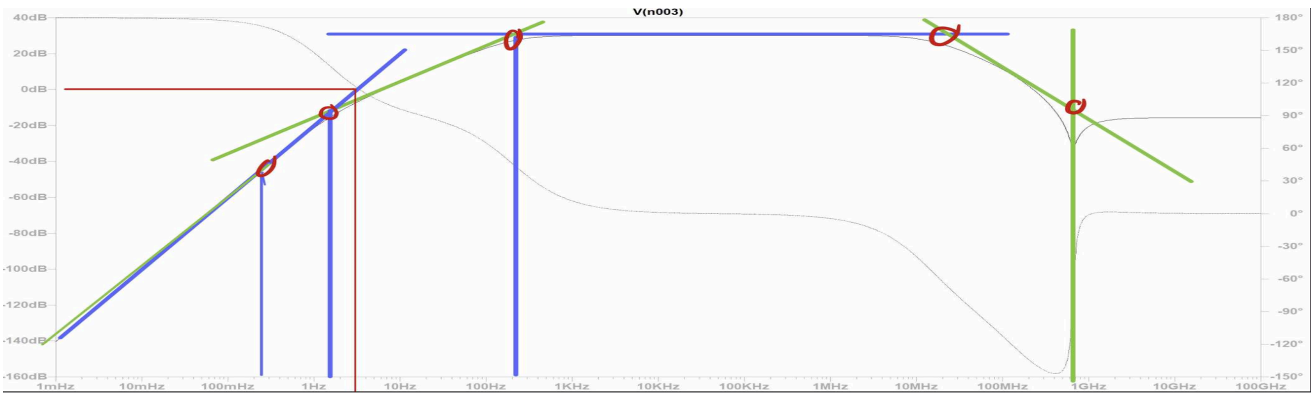


Figure 3.3.1A Bode Plot and Phase Diagram

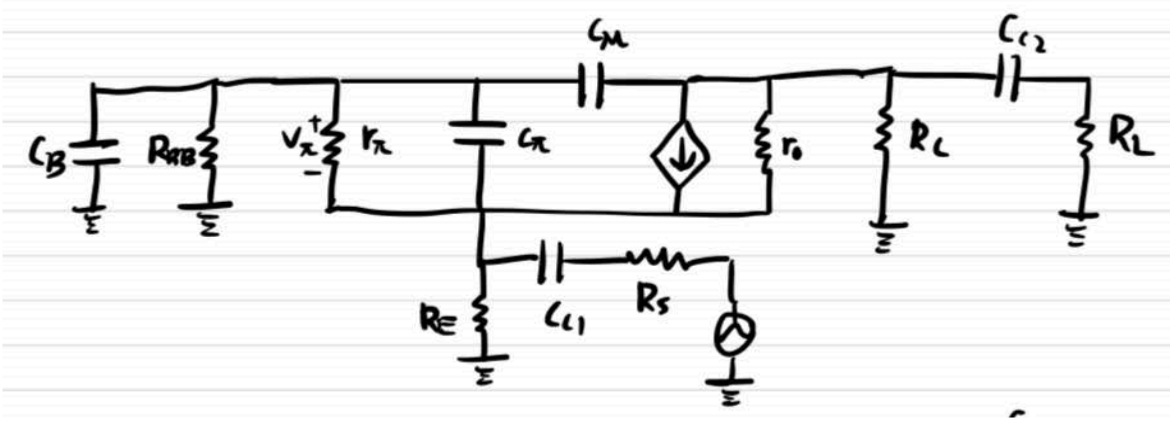


Figure 3.3.1 Complete Small-Signal Model

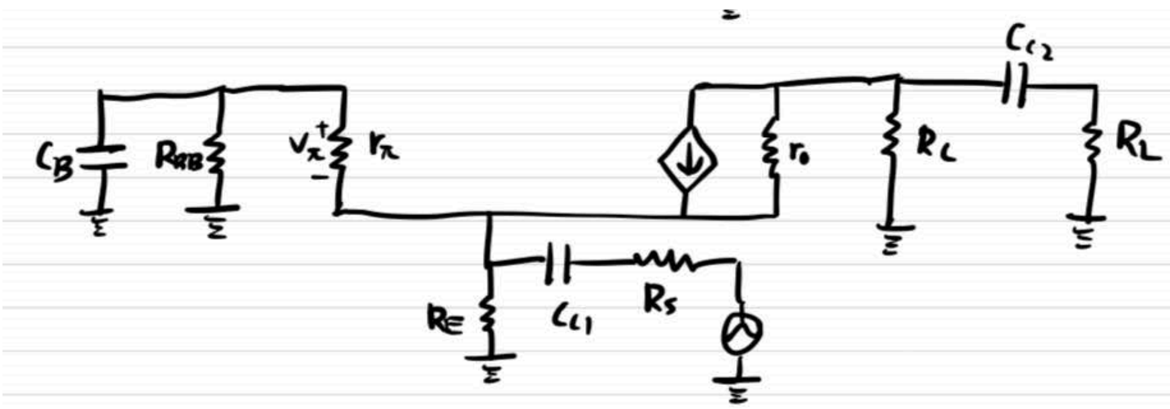


Figure 3.3.2 Low Frequency Model

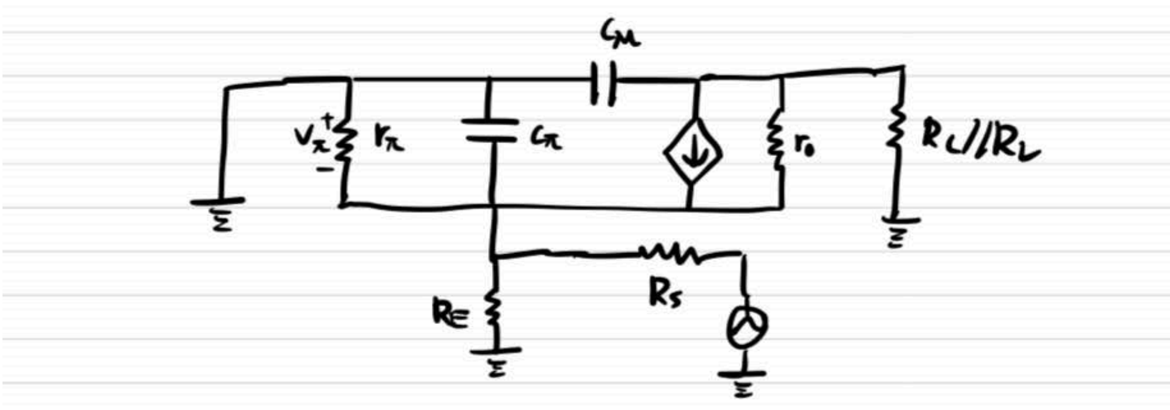


Figure 3.3.3 High Frequency Model

$$C_\pi \approx 2 * CJE + TF * gm \quad \text{and } C_\mu \approx \frac{CJC}{(1+\frac{V_{CB}}{VJC})^{MJC}}$$

From the datasheet, we found the value of C_π and C_μ used the given value.

2N2202-> $C_\pi \approx 18pF$ and $C_\mu \approx 5pF$, $\beta = 206.4$, $R_\pi = 5.16k\Omega$

Similarly with zero calculation, still two connected to the coupling capacitors thus resulting in a 0. And the last zero can be found by

$$\omega_{Lz3} = \frac{1}{R_{BB} * C_B}$$

For the low frequency poles, using the Figure 3.2.2, we generated the following equations

$$\text{OCTC} \rightarrow \omega^{C_1}_{Lp1} = \frac{1}{(R_{BB}||(R_\pi+(1+\beta)*R_E))*C_B}$$

$$\text{SCTC} \rightarrow \omega^{C_E}_{Lp2} = \frac{1}{(R_s+R_E||\frac{R_\pi}{1+\beta})*C_{c1}}$$

$$\text{SCTC} \rightarrow \omega^{C_2}_{Lp3} = \frac{1}{(R_L+R_C)*C_{c2}}$$

For the high frequency poles, using the Figure 3.2.3, we generated the rest equations

$$\omega^{C_{T1}}_{Hp1} = \frac{1}{(\frac{R_\pi}{1+\beta}||R_E||R_S)*C_\pi}$$

$$\omega^{C_{T2}}_{Hp2} = \frac{1}{(R_C||R_L)*C_\mu}$$

2N2202	ω_{Lz1}	ω_{Lz2}	ω_{Lz3}	ω_{Lp1}	ω_{Lp2}	ω_{Lp3}	ω_{Hz1}	ω_{Hz2}	ω_{Hp1}	ω_{Hp2}
$\omega_{calculate}$	0	0	2	2.111	1338.04	9.804	-	-	3357.02M	78.43M
$f_{calculate}$	0	0	0.318	0.336	212.955	1.560	-	-	534.286M	12.48M
$f_{simulate}$	-	-	6.58	0.325	208.43	2.048	∞	∞	653.847M	12.62M

3.3 B

Similarly as previous case, we redraw the circuit into mid-band form

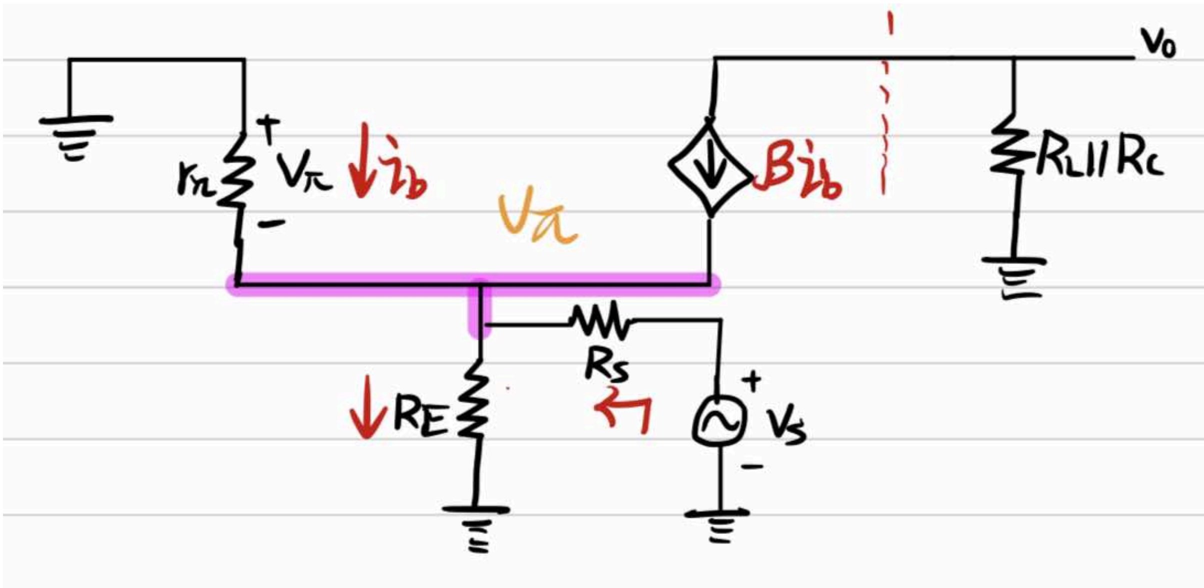


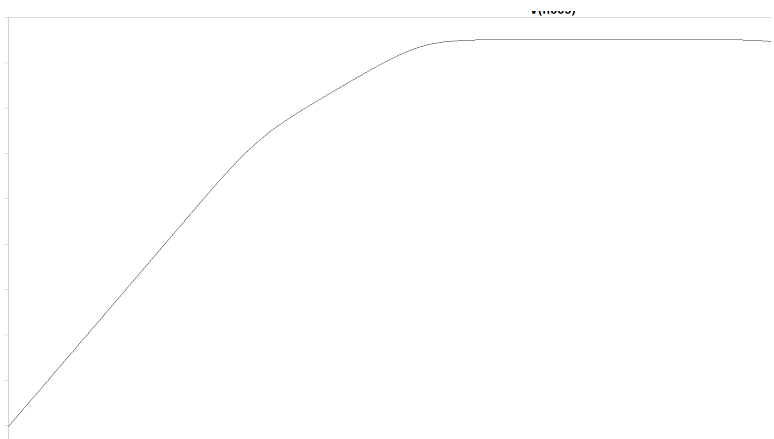
Figure 3.3.4 Mid-Band Gain circuit

After finding $\frac{V_o}{V_I}$ and simplified, we end up with

$$A_M = -gm * (R_C || R_L) * \frac{-\frac{R_\pi}{1+\beta}||R_E}{\frac{R_\pi}{1+\beta}||R_E + R_S}$$

	2N2202
Calculated	33.76

2N2202 - Midband



3.3 C

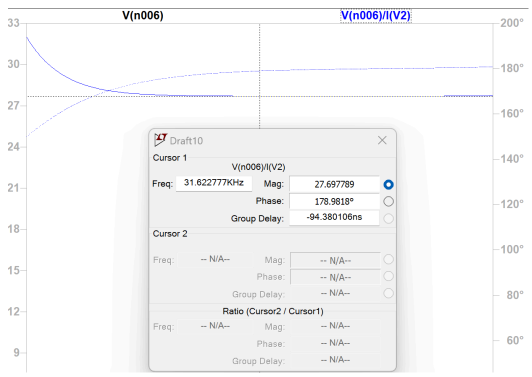
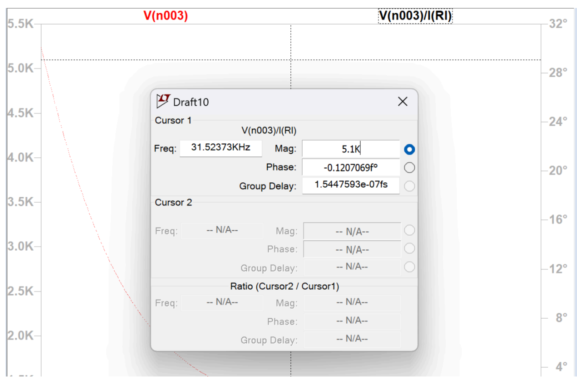
Input Impedance calculation $R_{in} = R_E || \frac{R_\pi}{1+\beta} = 24.736\Omega$

And simulated value equals to $R_{In} = 27.694\Omega$

3.3 D

Output Impedance calculation $R_{Out} = R_C = 5.1k\Omega$

And simulated value still equals to $R_{Out} = 5.1k\Omega$

Input Measured Value	Output Measured Value
	

4. Conclusion

In this project, we examined the DC operating points of three different transistors: the 2N3904, 2N4401, and 2N2222A. We also designed a bias network for these transistors in a common-emitter/common-base amplifier setup. Our research included an evaluation of the accuracy of small-signal models and their limitations when it comes to predicting high-frequency poles. What's more, we used the "1/3 Rule" for biassing and noted its practical parameters. This investigation provided us with valuable insights into biassing methods, the behaviour of transistors within amplifier circuits, and the trade-offs involved in modelling and analysis.

5. References

1. ELEC 301 Course Notes
2. A. Sedra and K.Smith, "Microelectronic Circuits", 8th (or higher) Ed., Oxford University Press, New York.
3. LTSPICE User's Tutorial
4. 2N2222A datasheet
5. 2N3904 datasheet
6. 2N4401 datasheet