Mini Project Two

ELEC 301

University of British Columbia

Submitted By:

Hanlin Yu

36958502

2024/10/20

Professor:

Nicolas Jaeger

Content

1 Introduction 1
2 Part I 1
a) 1
b) 1
i) 1
ii) 2
iii) 2
Comparison 3
c) 3
i) 3
ii) 4
iii) 5
iv) 5
d) 5
Observation: 5
3 Part II 6
a) 6
Simulated: 6
Calculated: 6
ZEROS: 7
Poles: 7
Comparison: 8
The 2N4401 transistor: 8
Comparison: 9
b) 10
c) 10
d) 11

e) 12
4 Part III 12
a) 12
b) 14
c) 14
d) 14
Conclusion 15
References 15
Appendix: 16
Appendix 1: Part I c): bias circuit i) , bias circuit ii) and bias circuit iii) 16
Appendix 2 bias circuit: Bias circuit for 2N3904 and 2N4401 16
Appendix 3 Part II a) Circuit simulation of 2N3904 and circuit diagram for testing output impedance: 16
Appendix 4 High frequency and low frequency small signal model 16
Appendix 5 part III a) Small signal circuit and High frequency model : 17
Appendix 6. Circuit for input impedance and output impedance. 17

Figure 1 Circuit diagram and simulation for $IB\ VS\ VBE$ 1
Figure 2 Circuit diagram and simulation for $Ic\ VS\ VCE$ 2
Figure 3 Circuit diagram and plot for $Ic\ VS\ VCE$ 2
Figure 4 $iC\ VS\ VBE$ with $VCE = 5V\ and\ Ic = 1mA$ 2
Figure 5 $Ic\ VS\ VCE$ with $VBE = 0.6V$ 3
Figure 6 Linear approximation and bode plots of magnitude and phase 6
Figure 7 small signal circuit for 2N3904 7
Figure 8 2N4401 bode plots for magnitude and phase 8
Figure 9 Bode plot and voltage transfer function of 2N3904 10
Figure 10Voltage transfer function of 2N4401 10
Figure 11Bode plots and circuit diagram of 2N2222A 12
Figure 12 Voltage transfer function of2N2222A 14

Table 2a.1 Parameter's value 1
Table 2 Datasheet and calculated comparison..3
Table 3 DC operation point i) 4
Table 4 DC operation point ii) 4
Table 5 DC operation point ii) 5
Table 6 Dc operating point..5
Table 7 poles and zeros 2N3904..8
Table 8 Input impedance..11
Table 9 Output impedance 11
Table 10 Poles and zeros for 2N2222A 13
Table 11 Input impedance 14
Table 12 Output impedance..15

1 Introduction

This project focuses on the design, analysis, and simulation of transistor circuits using both theoretical calculations and practical simulations. Transistors, particularly the 2N2222A, 2N3904, and 2N4401.The objective of this work is to examine parameters in various biasing circuits, simulate their behavior under different conditions, and compare the results with theoretical calculations.

2 Part I

a)

Look up the datasheet from “ON Semiconductor” of the 2N2222A transistor. Find the values of the small signal parameters h_{fe}, h_{ie}, h_{oc} for $V_{CE} = 10V, I_c = 1mA, f = 1kHz, and\ T = 25℃$ (Bias point).

Description	Symbol	Small signal parameters	Min	Max	Mean
Input Impedance	h_{ie}	r_π	$2.0k\Omega$	$8.0k\Omega$	$5.0k\Omega$
Small−Signal Current Gain	h_{fe}	β	50	300	175
Output Admittance	h_{oe}	$\frac{1}{r_o}$	$5.0\mu℧$	$35\mu℧$	$20\mu℧$

Table 2a.1 Parameter's value

At specific bias point: $\boldsymbol{h_{ie} = r_\pi = 5.0k\Omega, h_{fe} = h_{FE} = 175, h_{oe} = 20\mu℧}$**.**

b)

i)

Simulate the circuit in CircuitMaker software. Sweep the voltage of V_{BE} from 0V to 3V with increments of 10mV and plot the graph of $I_B\ VS\ V_{BE}$.

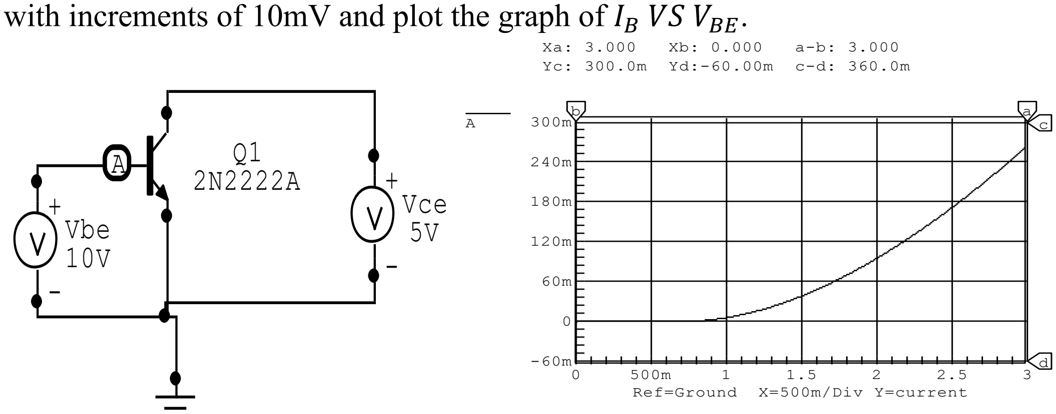


Figure 1 Circuit diagram and simulation for $I_B\ VS\ V_{BE}\ (V_{CE} = 5V)$

ii)

To plot I_c VS V_{CE}, draw the following circuit diagram and sweep V_{CE} from 0V to 10V with increments of 100mV while sweep I_B from $0\mu A$ to $15\mu A$ with increments of $0.5\mu A$.

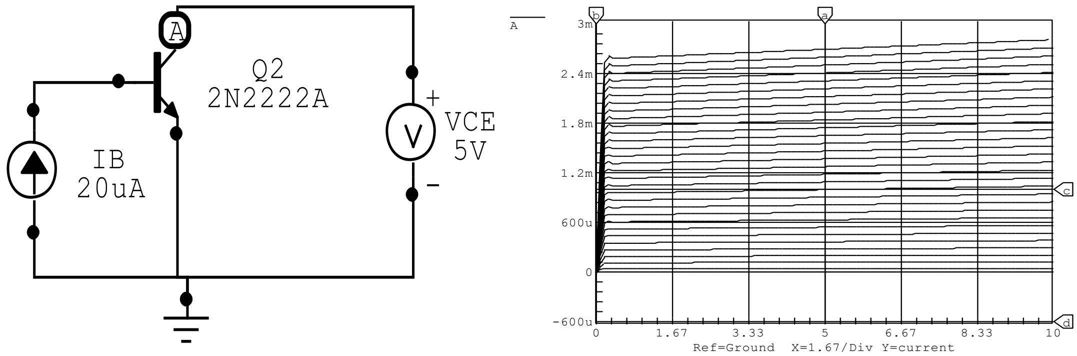


Figure 2 Circuit diagram and simulation for I_c VS V_{CE}

iii) Sweep V_{BE} from 0V to 3V with increments of 0.1V while V_{CE} is swept from 0V to 10 V with increments of 0.1V. Plot for I_c VS V_{CE}.

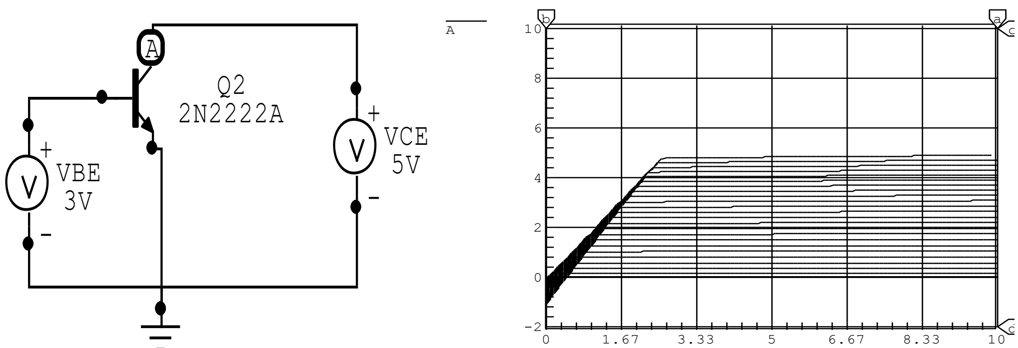


Figure 3 Circuit diagram and plot for I_c VS V_{CE}.

From figure 2, we can find the intersection when V_{CE} is 5V and I_C = 1mA, it is the 13th line with increments of $0.5\mu A$, which is $6.0\mu A$. So $I_B = 6.0\mu A$. $\boldsymbol{\beta} = \frac{\boldsymbol{I_C}}{\boldsymbol{I_B}} = \boxed{\mathbf{166.667}}$. For g_m we need use "Figure 1" but plot I_c VS V_{BE} instead and set V_{CE} to 5V. We find the slope when $i_C = 1mA$.

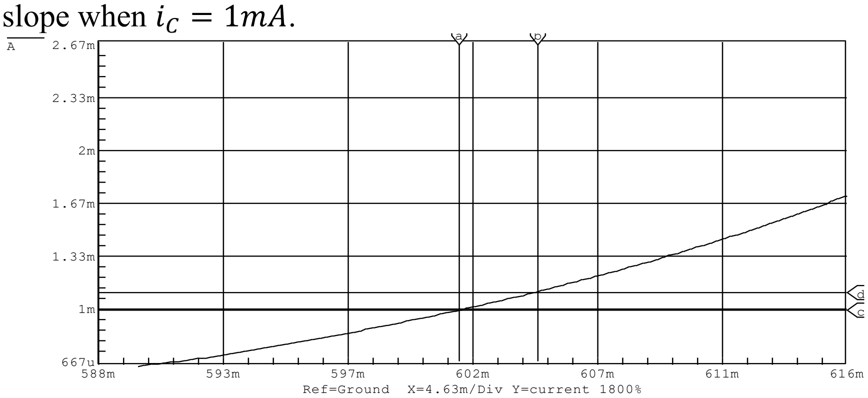


Figure 4 i_C VS V_{BE} with $V_{CE} = 5V$ and $I_c = 1mA$.

$\boldsymbol{g_m = \frac{\partial i_c}{\partial V_{BE}}|_{i_C=I_C} = \frac{0.1086mA}{2.906mV} = \boxed{0.03737}℧.\ r_\pi = \frac{\beta}{g_m} = \boxed{4459.9}\Omega}$.

Then try to find r_o $using\ formula\ \frac{\partial i_C}{\partial v_{CE}|_{v_{BE}=0.6V}}^{-1}$. Use the circuit diagram from "Figure 3" to plot $I_c\ VS\ V_{CE}$. When $\boldsymbol{V_{BE} = 0.6V}$,the point of $V_{CE} = 5V\ and I_c = 1$mA is about on the line so it is the line to find r_o. Below figure can better explain the reason.

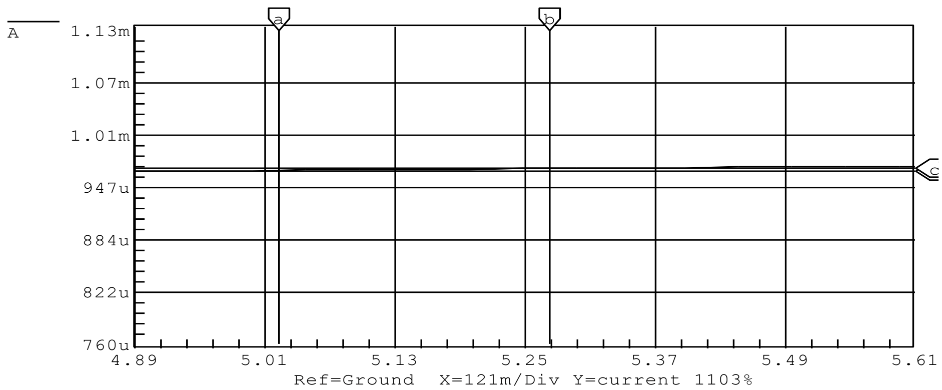


Figure 5 $I_c\ VS\ V_{CE}\ with\ V_{BE} = 0.6V$

So $\boldsymbol{r_o = \frac{\Delta i_C}{\Delta v_{CE}}^{-1} = \frac{3.456\mu A}{250.4mV}^{-1} = \boxed{72.411}k\Omega.\ h_{oe} = \frac{1}{r_o} = 13.8\mu℧.}$

Estimate V_A :

$$\boldsymbol{V_A = r_o * I_C = 72.411k\Omega * 1mA = \boxed{72.411}V}$$

Comparison

Symbol	Small signal parameters	Datasheet value Min	Datasheet value Max	Datasheet value Mean	Measured value	Error
h_{ie}	r_π	$2.0k\Omega$	$8.0k\Omega$	$5.0k\Omega$	$4.4599k\Omega$	10.88%
h_{fe}	β	50	300	175	166.667	4.76%
h_{oe}	$\frac{1}{r_o}$	$5.0\mu℧$	$35\mu℧$	$20\mu℧$	$13.8\mu℧$	31%

Table 2 Datasheet and calculated comparison

The measured data are all within the datasheet value range, and the input impedance values and small-signal current gain are close to the datasheet value mean.

$Error = \frac{|Measured\ value - Datasheet\ value\ mean\ |}{Datasheet\ value\ mean} * 100\%.$

c)

<u>Check Appendix 1: Part I c): bias circuit i) , bias circuit ii) and bias circuit iii) for detailed circuit diagram for question i),ii),iii).</u>

i)

Data for bias circuit:

$$V_{CE} = 4V, R_E = \frac{R_C}{2}, V_{CC} = 15V, \boldsymbol{I_C = 1mA}, \beta = 166.667, \boldsymbol{I_E} = \frac{\boldsymbol{\beta + 1}}{\boldsymbol{\beta}}\boldsymbol{I_C}, V_{BE} = 0.6V$$

For the right part of the circuit the voltage drop is$V_{CC} - V_{CE} = 11$V and current is $I_C = 1mA$.

So: $V_{CC} - V_{CE} = I_E * \frac{R_C}{2} + I_C R_C$, Solve to get $R_C = \boxed{7.319} k\Omega$ and $R_E = \boxed{3.659} k\Omega$.

$V_E = I_E * R_E = \boldsymbol{3.68V}, V_C = \boldsymbol{7.68V.}$

Now approach I_B, $\beta * I_B = I_C$, Solve to get $\boldsymbol{I_B = 6\mu A}$.

Also $V_B = V_{BE} + V_E = V_{BE} + I_E * R_E = 0.6V + 1mA * \frac{166.667+1}{166.667} * 3.659k\Omega = \boldsymbol{4.28}$V.

For the left part, use KCL:

$\frac{V_{CC}-V_B}{R_{B1}} = I_B + \frac{V_B}{R_{B2}}$, get: $R_{B1} = \frac{10.72*R_{B2}}{6*10^{-6}*R_{B2}+4.28}$.

Set $R_{B2} = \boxed{1k\Omega}$, get $R_{B1} = \boxed{2.5k\Omega}$.

Then, measure DC operating point using Figure 6 bias circuit i) for simulation on Circuitmaker:

V_B	I_B	V_C	I_C	V_E	I_E
4.28V	6.04μA	7.68V	1.00mA	3.68V	1.006mA

Table 3 DC operation point i)

In the simuation, $V_{CE} = 4V$, *and all other simulation data are also close to calculated data.*

ii)

Use 1/3 rule to bias the circuit:

$V_{CC} = 15V, I_C = 1mA, \beta = 166.667\frac{A}{A}, V_{BE} = 0.6V, I_E = \frac{\beta+1}{\beta} I_C = 1.006mA$.

$V_C = \frac{2}{3} V_{CC} = 10V, V_E = \frac{1}{3} V_{CC} = 5V, I_1 = \frac{I_E}{\sqrt{\beta}} = 77.92\mu A, I_B = \frac{I_C}{\beta} = 6\mu A, V_B = 5.6V.$

Given value above, calculate value of resistors:

$R_C = \frac{V_{CC}-V_C}{I_C} = \boxed{5k\Omega}, R_E = \frac{V_E - 0}{I_E} = \boxed{4.97k\Omega}. R_{B1} = \frac{V_{CC}-V_B}{I_1} = \frac{V_{CC}-(V_E+V_{BE})}{I_1} = \boxed{120.609k\Omega}$. $I_1 = I_B + \frac{V_E+V_{BE}-0}{R_{B2}}$, Solve to get $R_{B2} = \boxed{77.864k\Omega}$.

Then run a circuit simulation to measure DC operating point, Figure 6 bias circuit ii):

V_B	I_B	V_C	I_C	V_E	I_E
5.6V	5.99μA	10V	1.00mA	5V	1.006mA

Table 4 DC operation point ii)

iii)

Use resistors from "Standard Resistor and Capacitor Values" to replace ii) resistors.

$$R_C = 5.1k\Omega, R_E = 5.1k\Omega, R_{B1} = 120k\Omega, R_{B2} = 75k\Omega$$

Then run a circuit simulation to measure DC operating point, Figure 6 bias circuit iii):

V_B	I_B	V_C	I_C	V_E	I_E
5.5V	$5.741\mu A$	10.1V	0.956mA	4.9V	0.961mA

Table 5 DC operation point ii)

iv)

Observation:

The differences in the DC operating points between the three methods are small, especially between parts ii) and iii). The 1/3 rule provides an efficient and doable design approach, and when moving to real components (part iii), the deviations are within acceptable ranges. The results from part i) are also consistent with the expectations, as the biasing is done for a lower V_{CE}, leading to lower voltages at the base and collector.These small deviations are primarily due to the standard resistor values not exactly matching the theoretical calculations. Nonetheless, all three methods keep the transistor in its active region, which is the goal of the biasing circuit.

d)

Use the circuit obtained for parts c-iii) and replace with the 2N3904, and 2N4401. See "Appendix 2 Bias circuit for 2N3904 and 2N4401" to check 2N4401 circuit diagram and 2N3904 diagram.

Then run circuit simulation on CircuitMaker to get the dc operating point. Then use the same way as Part 1 b) to get the r_π, g_m, β.

Type	V_B	I_B	V_C	I_C	V_E	I_E	r_π	β	g_m
2N2222A	5.5 V	5.741 μA	10.1 V	0.956mA	4.9 V	0.961 mA	4.4599 $k\Omega$	166.667	0.03737 ℧
2N3904	5.4 V	7.91 μA	10.28 V	0.9257 mA	4.76 V	0.9334 mA	3.160556 $k\Omega$	117.029	0.037028℧
2N4401	5.47 V	6.484 μA	10.2 V	0.9399 mA	4.81 V	0.9464 mA	3.8556 $k\Omega$	144.9568	0.037596℧

Table 6 DC operating point

Observation:

Can observe that even use the closest commonly available resistors and different transistors, still satisfy the requirement of $V_{CC} = 15V$ and $I_C = 1mA$ and the dc operating point is consistent with only slight variation due to individual electrical characteristics. Select the transistor depending on the requirements and 2N2222A has higher β.

3 Part II

a)

Simulated:

First run the circuit simulation of 2N3904 on CircuitMaker. **<u>Check "Appendix 3 Part II a) Circuit simulation of 2N3904 and circuit diagram for testing output impedance" for circuit diagram.</u>**

Then show the magnitude and phase bode plots with sufficient bandwidth.

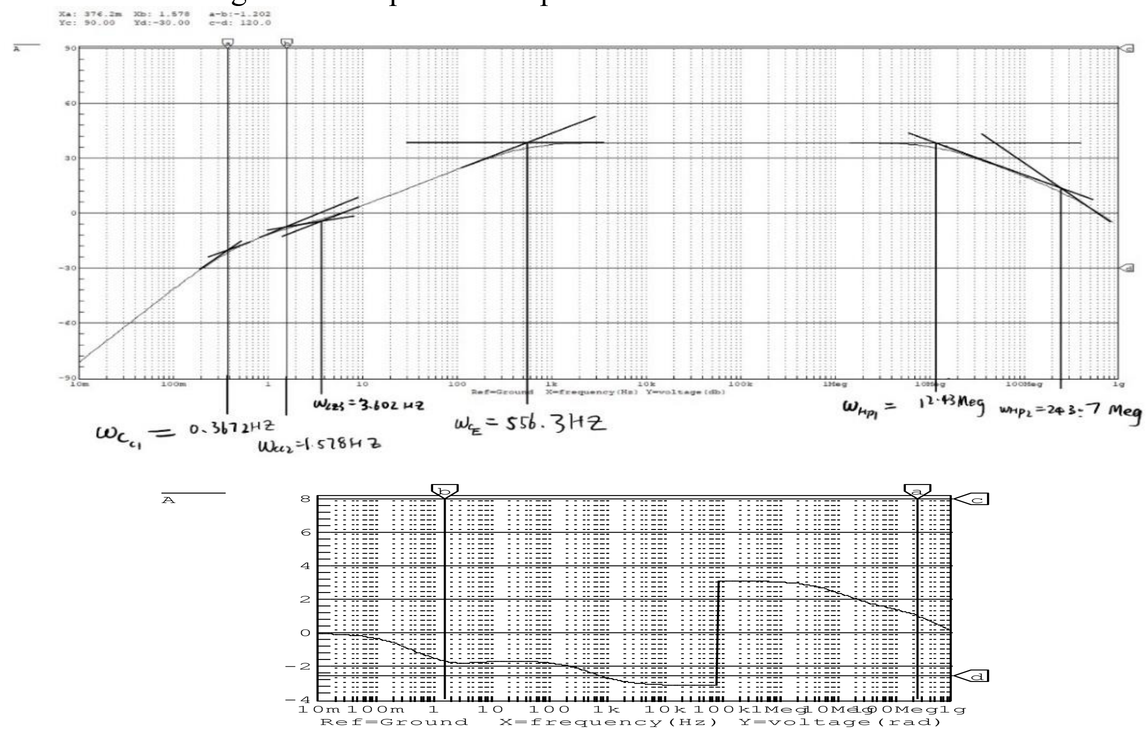


Figure 6 Linear approximation and bode plots of magnitude and phase

Use linear approximation to find the poles and zeros(marked the zeros and poles on the bode plots and their numerical value). From the plots can conclude. $\omega_{LZ1} = \omega_{LZ2} = 0\frac{1}{sec}, \omega_{LZ3} = 3.602 * 2 * \pi = 22.632\frac{1}{sec}, \omega_{C_{C1}} = 2.307\frac{1}{sec},$

$\omega_{C_{C2}} = 9.915\frac{1}{sec}, \omega_{C_E} = 3495.34\frac{1}{sec}, \omega_{Hp1} = 78.1 * 10^6\frac{1}{sec}, \omega_{Hp2} = 1531.21 * 10^6\frac{1}{sec}.$

Calculated:

Use the parameters from CircuitMaker, $C_\pi \approx 2 * CJE + TF * g_m = 23.808pF.$

$C_\mu \approx \frac{CJC}{\left(1+\frac{V_{CB}}{VJC}\right)^{MJC}} = 1.7996pF. \beta = 117.029.$

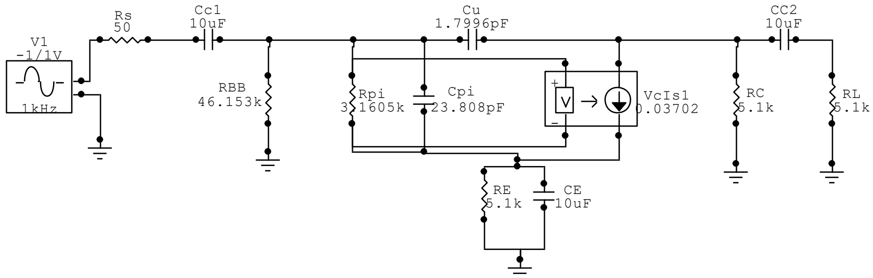


Figure 7 small signal circuit for 2N3904

Use the small signal circuit diagram to determine all the poles and zeros.

ZEROS:

Two of the zeros are due to $C_{C1}$and C_{C2} and located at s=0, $\boxed{\omega_{Lz1} = 0 \; and \; \omega_{Lz2} = 0}$. The third zero is founded by $i_b = 0$ and this happens when $Y_E = \frac{1}{R_E} + s_z C_E = 0$. $s_z = -\frac{1}{R_E C_E}$.

$\boxed{\omega_{Lz3} = \frac{1}{R_E C_E} = 19.6078 \frac{rad}{sec}}$.

Poles:

High frequency poles: Check “Appendix 4 part II a) High-frequency and low-frequency small-signal model” for circuit diagram.

The miller gain is $k = \frac{V_o}{V_\pi} = -g_m * R_C || R_L = -0.03702 * 2550\Omega = \boxed{-94.401}$.

From the circuit diagram we can observe two high frequency poles.

$\omega_{Hp1} = \tau_{Hp1}^{-1} = \frac{1}{R_{BB}||r_\pi||R_S(c_\pi + c_\mu(1-k))} = \boxed{1.04 * 10^8} \frac{rad}{s}$. $\omega_{Hp2} = \tau_{Hp2}^{-1} = \frac{1}{R_C||R_L * C_\mu * (1-\frac{1}{k})} = \boxed{2.1563 * 10^8} \frac{rad}{s}$.

Low frequency poles: Check “Appendix 4 part II a) High-frequency and low-frequency small-signal model” for circuit diagram.

Since the output is decoupled from the input, one of the pole is associated with C_{C2}. $\omega_{C_{C2}} = \tau_{C_{C2}}{}^{-1} = \frac{1}{(R_C + R_L) * C_{C2}} = \boxed{9.8039} \frac{rad}{s}$.

Then do the short circuit test. First, replace C_E with short circuit.

$\omega_{C_{C1}}{}^{SC} = \tau_{C_{C1}}{}^{-1} = \frac{1}{(R_S + R_{BB}||r_\pi) * C_{C1}} = 33.246 \frac{rad}{s}$.

Then replace $C_{C1}$with short circuit.

$\omega_{C_E}{}^{SC} = \tau_{C_E}{}^{-1} = \frac{1}{(R_E || (\frac{r_\pi + R_{BB}||R_S}{1+\beta})) * C_E} = \boxed{3696} \frac{rad}{s}$.

Since use the short circuit time constant, $\omega_{C_E} > \omega_{C_{C1}}$, then ω_{C_E}=3696 is correct.

Then replace C_E with open circuit $\omega_{C_{C1}}{}^{OC} = \tau_{C_{C1}}{}^{-1} = \frac{1}{((R_S+R_{BB}||(r_\pi+(1+\beta)R_E))*C_{C1}} = \boxed{2.32925}\frac{rad}{sec}$.

Comparison:

	$\omega_{LZ1}\frac{1}{sec}$	$\omega_{LZ2}\frac{1}{sec}$	$\omega_{LZ3}\frac{1}{sec}$	$\omega_{C_{C1}}\frac{1}{sec}$	$\omega_{C_{C2}}\frac{1}{sec}$	$\omega_{C_E}\frac{1}{sec}$	$\omega_{Hp1}\frac{1}{sec}$	$\omega_{Hp2}\frac{1}{sec}$
Simulated	0	0	22.632	2.307	9.915	3495.3	$78.1 * 10^6$	$1531.21 * 10^6$
Calculated	0	0	19.6078	2.32925	9.8039	3696	$1.04 * 10^8$	$2.1563 * 10^8$
Percent Error	0	0	13.362 %	0.96%	1.12%	5.74%	33.16%	85.92%

Table 7 poles and zeros 2N3904.

The percent error is calculated by $\frac{|Simulated|-|Calculated|}{|Simulated|} * 100\%$ (The following question use the same formula to calculate error). The error of low-frequency poles and zeros is fairly small but the error of high-frequency poles is high because of the Miller transformation.

The 2N4401 transistor:

Simulated:

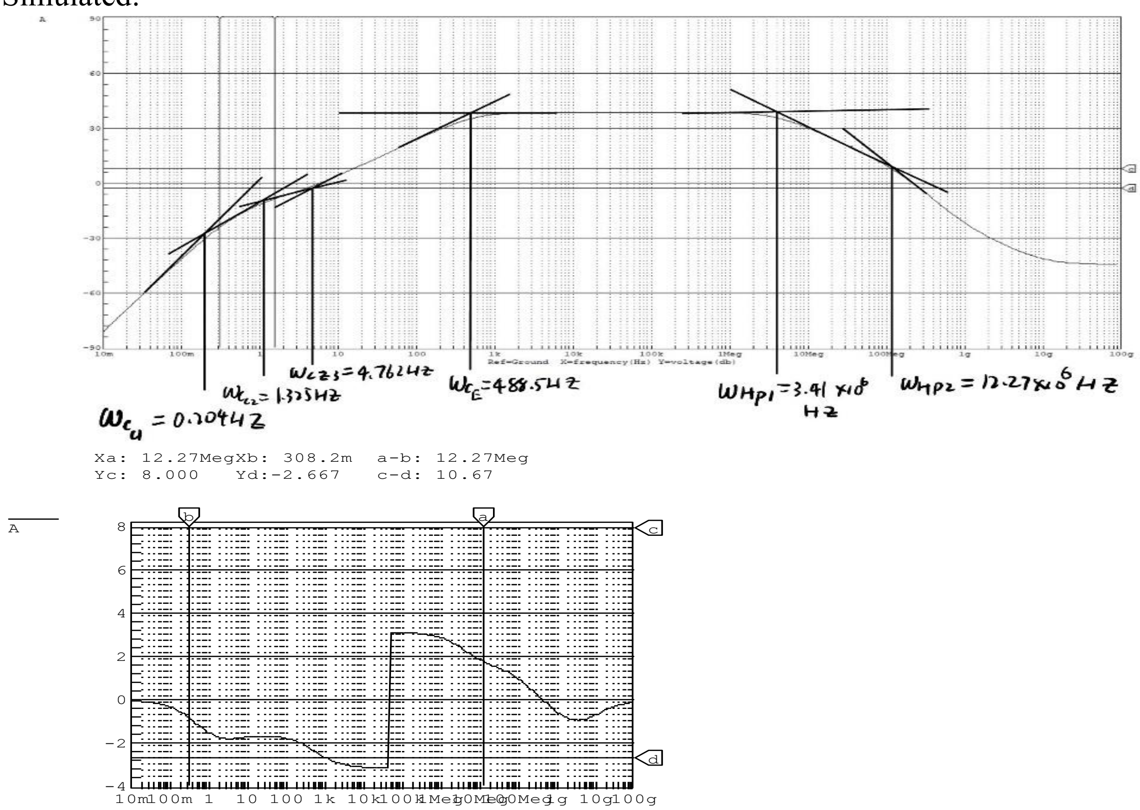


Figure 7 2N4401 bode plots for magnitude and phase

Plot the Bode plots for magnitude and phase to identify using linear approximation. $\omega_{C_{C1}} = 0.204Hz * 2 * \pi = 1.268 \frac{1}{rad}, \omega_{C_{C2}} = 8.325 \frac{1}{rad}, \omega_{C_{LZ3}} = 29.36 \frac{1}{rad}, \omega_{C_E} = 3069.34 \frac{1}{rad}, \omega_{Hp1} = 2.14 * 10^7 \frac{1}{rad}, \omega_{Hp2} = 7.71 * 10^7 \frac{1}{rad}$.

Calculated:

Use the same way to get: $C_\pi \approx 2 * CJE + TF * g_m = 66.05pF$.

$C_\mu \approx \frac{CJC}{\left(1+\frac{V_{CB}}{VJC}\right)^{MJC}} = 5.285pF$. $\beta = 144.029$. r_π =3.8556 $k\Omega$.

The approach to get poles is the same but the numerical values will change, so use the same formula to calculate poles.

The zeros are the same: $\boxed{\omega_{Lz1} = 0 \text{ and } \omega_{Lz2} = 0}$. $\boxed{\omega_{Lz3} = \frac{1}{R_E C_E} = 19.6078 \frac{rad}{sec}}$.

Then calculate high frequency poles:

$k = \frac{V_o}{V_\pi} = -g_m * R_C||R_L = -0.037596 * 2550\Omega = \boxed{-95.8698}$.

$\omega_{Hp1} = \tau_{Hp1}^{-1} = \frac{1}{R_{BB}||r_\pi||R_S(c_\pi + c_\mu(1-k))} = \boxed{3.5088 * 10^7} \frac{rad}{s}$. $\omega_{Hp2} = \tau_{Hp2}^{-1} = \frac{1}{R_C||R_L * C_\mu * (1-\frac{1}{k})} = \boxed{7.3436 * 10^7} \frac{rad}{s}$.

Low frequency poles:

$\omega_{C_{C2}} = \tau_{C_{C2}}{}^{-1} = \frac{1}{(R_C+R_L)*C_{C2}} = \boxed{9.8039} \frac{rad}{s}$. $\omega_{C_E}{}^{SC} = \tau_{C_E}{}^{-1} = \frac{1}{(R_E||(\frac{r_\pi + R_{BB}||R_S}{1+\beta}))*C_E} = \boxed{3733.02} \frac{rad}{s}$. $\omega_{C_{C1}}{}^{OC} = \tau_{C_{C1}}{}^{-1} = \frac{1}{((R_S+R_{BB}||(r_\pi+(1+\beta)R_E))*C_{C1}} = \boxed{2.2987} \frac{rad}{s}$.

Comparison:

	$\omega_{LZ1} \frac{1}{sec}$	$\omega_{LZ2} \frac{1}{sec}$	$\omega_{LZ3} \frac{1}{sec}$	$\omega_{C_{C1}} \frac{1}{sec}$	$\omega_{C_{C2}} \frac{1}{sec}$	$\omega_{C_E} \frac{1}{sec}$	$\omega_{Hp1} \frac{1}{sec}$	$\omega_{Hp2} \frac{1}{sec}$
Simulated	0	0	29.36	1.268	8.325	3069.34	$2.14 * 10^7$	$7.71 * 10^7$
Calculated	0	0	19.6078	2.2987	9.8039	3733.02	$3.5088 * 10^7$	$7.3436 * 10^7$
Percent Error	0	0	33%	81.285 %	15.08 %	21.6%	63.963 %	4.752%

Table 8 Poles and zeros of 2N4401

The percent error in low-frequency poles and zeros is because their frequencies are close, linear approximation becomes not precise due to the slope is not $-20dB$ or $-40dB$. The highest pole is consistent.

b)

2N3904 voltage gain:

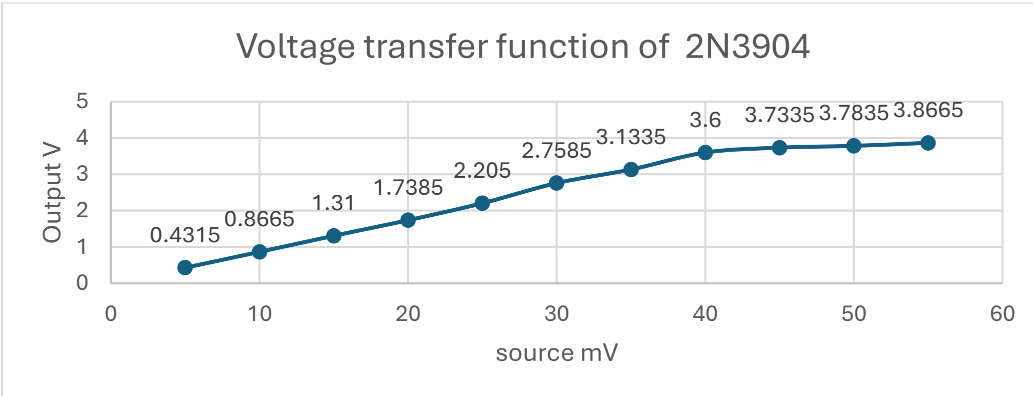


Figure 8 Bode plot and voltage transfer function of 2N3904

Use the bode plot to pick the middle of mid-band frequency of 2N3904, which is $\omega = 619987\frac{1}{rad}$, f1=98674Hz (cursor "a" on the bode plot). Set the source frequency to f1 and sweep the voltage from 5mV until turning point. Increase the voltage by 5mV each time and save the output voltage. Then plot the graph of Output VS source using excel. The turning point where the line becomes not linear is somewhere between 40mV for 2N3904.

2N4401voltage gain:

For the 2N4401, the bode plot shows that the middle of the mid-band gain is about 60.68kHz. Set the source frequency to 60.68kHz. Sweep the voltage source and measure the output voltage. Use the excel to plot the diagram.

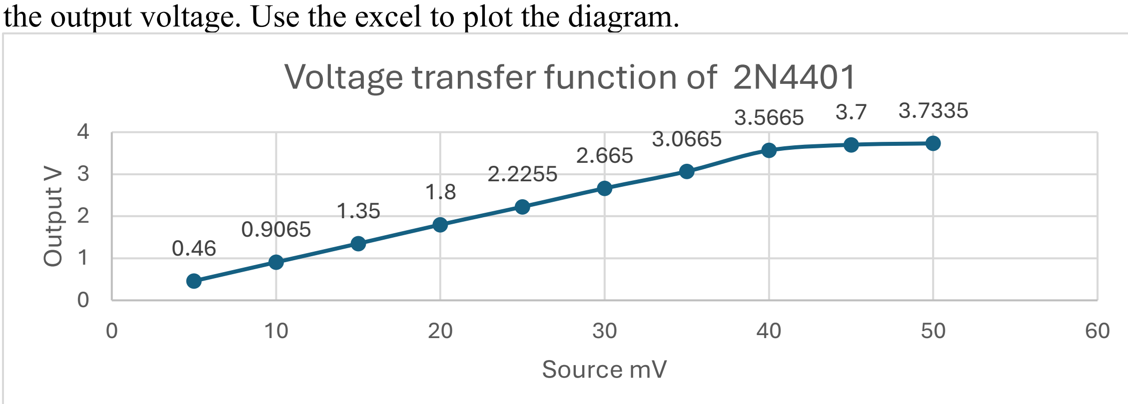


Figure 9 Voltage transfer function of 2N4401

The chart shows that when the source voltage is about 40mV, the line is not linear for 2N4401.

c)

At mid-band frequency, the high-frequency capacitors are open circuits, and the low-frequency capacitors are short circuits. Then use the "Figure 11" and replace the

C_π *and* C_μ with open circuit. Then the input impedence is $R_{B1}||R_{B2}||r_\pi$ excluding source resistance.

Calculated input resistance of 2N3904, $R_{in} = R_{B1}||R_{B2}||r_{\pi(2N3904)} = 2.95756k\Omega$.

Calculated input resistance of 2N4401, $R_{in} = R_{B1}||R_{B2}||r_{\pi(2N4401)} = 3.558k\Omega$.

Set the voltage source before the saturation point for simulated input resistance, which uses 20mV for both transistors. The frequency of the source is 98.674kHz and 60.68kHz for 2N3904 and 2N4401, respectively. Simulate the circuit on CircuitMaker and measure the V_{in} *and* I_{in}. $R_{in} = \frac{V_{in}}{I_{in}}$.

Simulated input resistance of 2N3904, $R_{in} = \frac{V_{in}}{I_{in}} = \frac{14.12mV}{4.199\mu A} = 3.3627k\Omega$

Simulated input resistance of 2N4401, $R_{in} = \frac{V_{in}}{I_{in}} = \frac{14.14mV}{4.312\mu A} = 3.4171k\Omega$.

Transistors	Calculated input resistance	Simulated input resistance	Percent error
2N3904	$2.95756k\Omega$	$3.3627k\Omega$	12.05%
2N4401	$3.558k\Omega$	$3.4171k\Omega$	4.126%

Table 8 Input impedance

The error between calculated resistance and simulated resistance is small.

d)

Same with part c), use the "Figure 11" and replace the capacitors with open circuit, the output resistance is $R_{out} = R_C$.

So the calculated resistance $R_{out(2N3904)} = R_{out(2N4401)} = R_C = 5.1k$.

Run the "Figure 8" 2N3904 circuit for testing output impedance. Short the input source and replace the R_L with $V_{test(\max)} = 20mV, f = 98.6kHz$.

Use the probe on CircuitMaker to measure the I_{test} and V_{test} Then the$R_{out} = \frac{V_{test}}{I_{test}}$.

Simulated: $R_{out(2N3904)} = \frac{V_{test}}{I_{test}} = \frac{14.12mV}{2.894\mu A} = 4.87906k\Omega$.

Use the similar circuit for 2N4401 with $V_{test(\max)} = 20mV, f = 60.68kHz$.

Simulated: $R_{out(2N4401)} = \frac{V_{test}}{I_{test}} = \frac{14.14mV}{2.887\mu A} = 4.8978k\Omega$.

Transistors	Calculated output resistance	Simulated output resistance	Percent error
2N3904	$5.1k\Omega$	$4.87906k\Omega$	4.5296%
2N4401	$5.1k\Omega$	$4.8978k\Omega$	4.128%

Table 9 Output impedance

The percent of error of output impedance is small .

e)

Using the results from part A, the bandwidth of 2N3904 is larger, which is about $7.8 * 10^7 \frac{1}{sec}$ while that of 2N4401 is about $2.4 * 10^7 \frac{1}{sec}$. The low-frequency poles and zeros for both transistors are close, so their performance of low frequency is similar, but 2N3904 has higher cut-off frequencies in high-frequency ranges, which suggests better performance in high frequency. <u>So, select 2N3904.</u>

4 Part III

a)

Simulated:

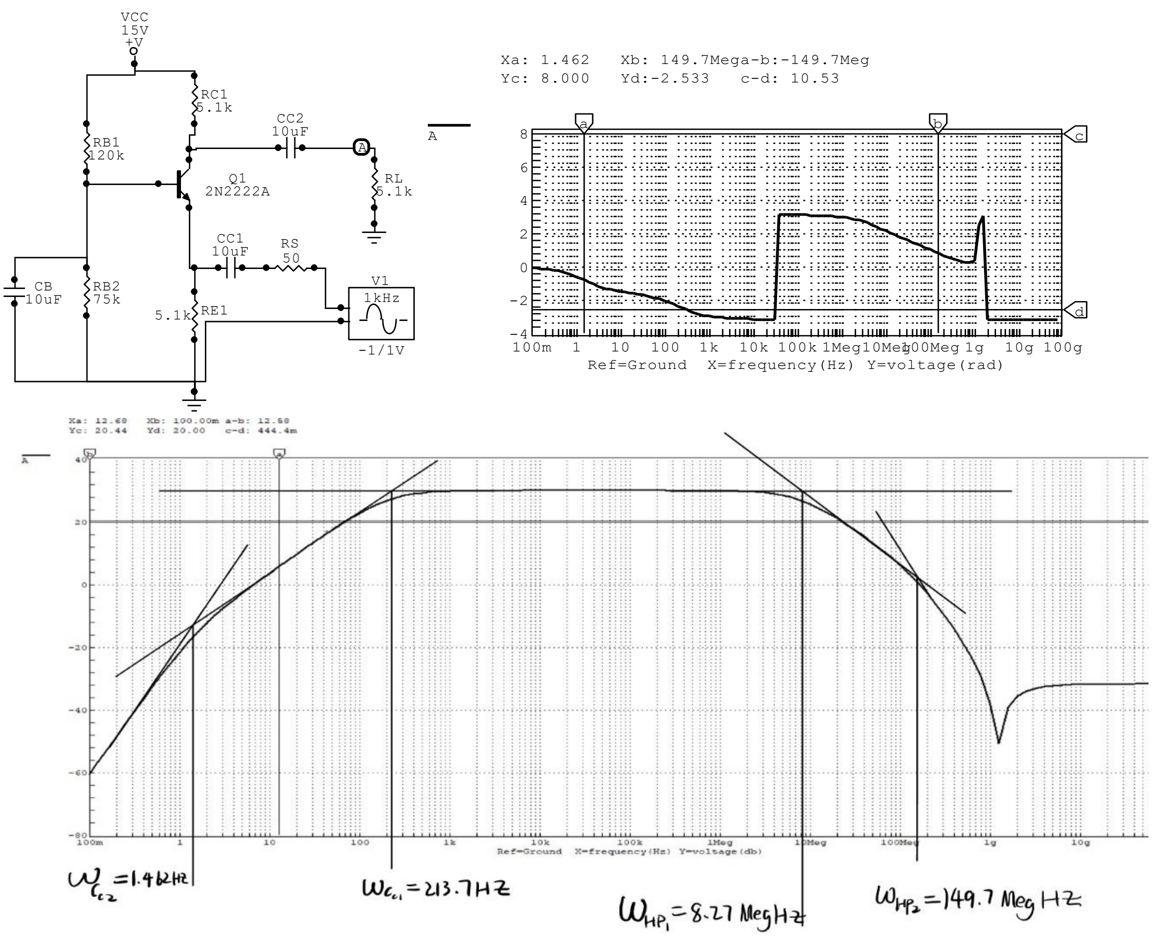


Figure 10Bode plots and circuit diagram of 2N2222A

Given the bode plots of magnitude and phase, use the linear approximation to obtain the poles and zeros $\omega_{C_{C2}} = 1.462Hz * 2 * \pi = 9.186 \frac{1}{rad}$, $\omega_{C_{C1}} = 1342.7167 \frac{1}{rad}$, $\omega_{Hp1} = 5.196 * 10^7 \frac{1}{rad}$, $\omega_{Hp2} = 9.406 * 10^8 \frac{1}{rad}$. $\omega_{LZ1} = \omega_{LZ1} = 0 \frac{1}{rad}$.

Since ω_{Lz3} is so close to ω_{C_B} that can not use linear approximation to find them.

Calculated: Check Appendix 5 for small signal circuit diagram

Use the parameters from CircuitMaker, $C_\pi \approx 2 * CJE + TF * g_m = 73.836pF$.

$C_\mu \approx \frac{CJC}{\left(1+\frac{V_{CB}}{VJC}\right)^{MJC}} = 7.94pF.\ \beta = 166.667.\ r_\pi = 4.459k\Omega.$

Zeros: From the circuit diagram, two of the zeros due to the coupling capacitors are located s=0, $\omega_{LZ1} = \omega_{LZ1} = 0\frac{1}{rad}$. The third one is at $i_b = 0A$. So, $Y_B = \frac{1}{R_{BB}} + s_z * C_B = 0$, get $\omega_{Lz3} = \frac{1}{R_{BB} * C_B} = \boxed{2.1667}\frac{1}{rad}$.

High frequency poles: Check Appendix 5 for high-frequency small signal circuit diagram

From the high frequency poles diagram. C_μ is grounded. Low frequency capacitors are shorted

$\omega_{Hp1} = \frac{1}{R_L || R_C * C_\mu} = \boxed{4.939 * 10^7}\frac{1}{sec}$.

For the other pole C_π, r_π is de-magnified so $\omega_{Hp2} = \frac{1}{\frac{r_\pi}{1+\beta}||R_E||R_S C_\pi} = \boxed{7.8279 * 10^8}\frac{1}{sec}$.

Low frequency poles: high frequency capacitors are open circuit.

$C_{c2}$is decoupled so one of the low frequency pole is $\omega_{C_{C2}} = \frac{1}{(R_C+R_L)C_{C2}} = \boxed{9.8039}\frac{1}{sec}$.

Use short circuit time constant and short C_{C1} firstly.

$\omega_{C_B}{}^{SC} = \frac{1}{(R_{BB}||(r_\pi+(1+\beta)(R_E||R_S)))C_B} = 10.003\frac{1}{sec}$.

Then short ω_{C_B}, $\omega_{C_{C1}}{}^{SC} = \frac{1}{(R_S+\frac{r_\pi}{1+\beta}||R_E)C_{C1}} = \boxed{1307.9346}\frac{1}{sec}$.

$\omega_{C_{C1}}{}^{SC} > \omega_{C_B}{}^{SC}$, then the second one is right and replace C_{C1} open circuit:

$\omega_{C_B}{}^{OC} = \frac{1}{(R_{BB}||(r_\pi+(1+\beta)(R_E)))C_B} = \boxed{2.283}\frac{1}{sec}$.

Comparison:

	$\omega_{Lz1}\frac{1}{sec}$	$\omega_{Lz2}\frac{1}{sec}$	$\omega_{Lz3}\frac{1}{sec}$	$\omega_{C_{C2}}\frac{1}{sec}$	$\omega_{C_B}\frac{1}{sec}$	$\omega_{C_{C1}}\frac{1}{sec}$	$\omega_{Hp1}\frac{1}{sec}$	$\omega_{Hp2}\frac{1}{sec}$
Simulated value	0	0	NA	9.186	NA	1342.72	$5.196 * 10^7$	$9.406 * 10^8$
Calculated value	0	0	2.1667	9.8039	2.283	1307.935	$4.939 * 10^7$	$7.8279 * 10^8$
error	0	0	NA	6.73%	NA	2.589 %	4.946%	16.78%

Table 10 Poles and zeros for 2N2222A

One pole and one zero can not be found because they are too close. The error of simulated and calculated value of other poles and zeros is small.

b)

From the bode plot of part a), the middle of mid band frequency is about 40.57kHz. Set the source to **40.57kHz**. Increase source voltage until the line is not linear.

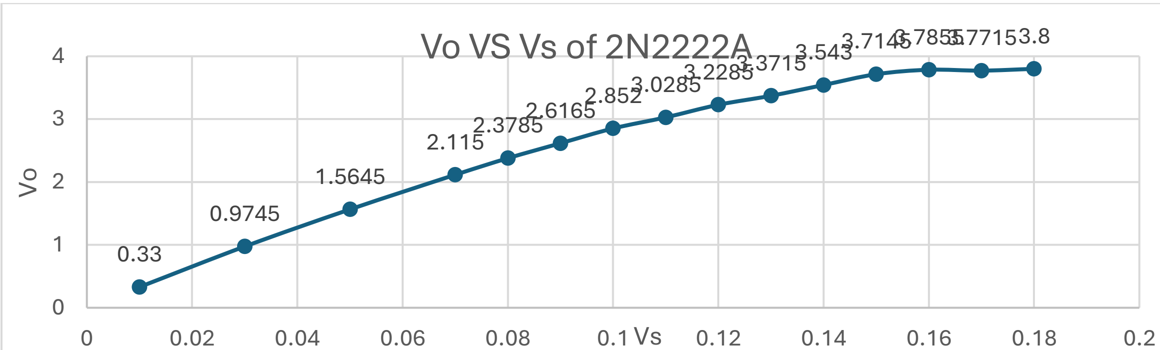


Figure 11 Voltage transfer function of2N2222A

Save the data of "V_S" and "V_{output}" and plot the graph on excel. The graph shows that when V_o is around **150mV**, the line becomes not linear.

c)

At the mid band, capacitors are open circuits and short circuits. Use the following diagram to get input impedance. $R_{in} = \frac{V_{test}}{I_{test}} = R_E || \frac{r_\pi}{1+\beta} = 26.456\Omega$**. Check Appendix 6 for circuit diagram.**

Simulated: Set the source to 110mV, 40.5kHz. Measure the V_{input} and I_{input}.

$$R_{in} = \frac{V_{input}}{I_{input}} = \frac{77.55mV}{2.721mA} = 28.5\Omega.$$

Transistors	Calculated input impedance	Simulated input impedance	Percent error
2N2222A	26.456Ω	28.5Ω	7.17%

Table 11 Input impedance

The error between calculated value and simulated value is small.

d)

The calculated output impedance is R_C because the output is decoupled. **Check Appendix 6 for circuit diagram**. $R_{out(calculated)} = R_C = 5.1k\Omega$.

Run the 2N2222A circuit for testing output impedence. Short the input source and replace the R_L with $V_{test(\max)} = 110mV, f = 40.5kHz$.

$$R_{out(simulated)} = \frac{V_{test}}{I_{test}} = \frac{77.66mV}{15.45\mu A} = 5.026k\Omega.$$

Transistors	Calculated output impedance	Simulated output impedance	Percent error
2N2222A	$5.1k\Omega$	$5.026k\Omega$	1.47%

Table 12 Output impedance

The percent error is small, with 1.47%.

Conclusion

This project analyzed and simulated transistor circuits, focusing on the 2N2222A, 2N3904, and 2N4401. The comparison of theoretical calculations with simulations revealed that small signal parameters and DC operating points closely aligned with datasheet values. This work emphasizes the importance of both theoretical understanding and practical testing in optimizing transistor circuit design for different applications. Determined poles, zeros, input impedance and output impedance of different transistors.

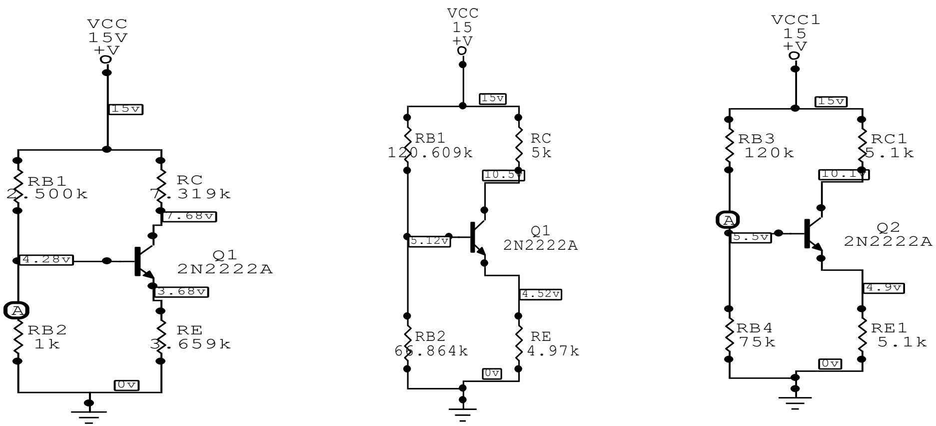
References

ELEC 301 Course Notes.
Standard Resistor and Capacitor Values List from the Other Mini Project Related Handouts Module on
CANVAS.
A. Sedra and K. Smith, "Microelectronic Circuits," 5th (or higher) Ed., Oxford University Press, New York.

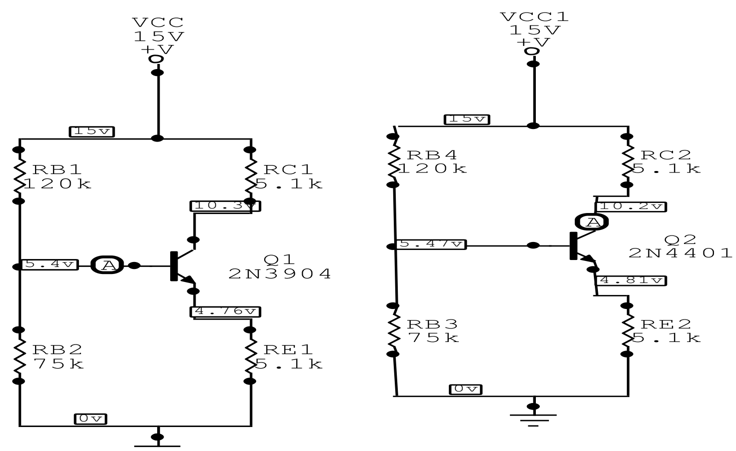
P2N2222A Amplifier Transistors - onsemi

Appendix:

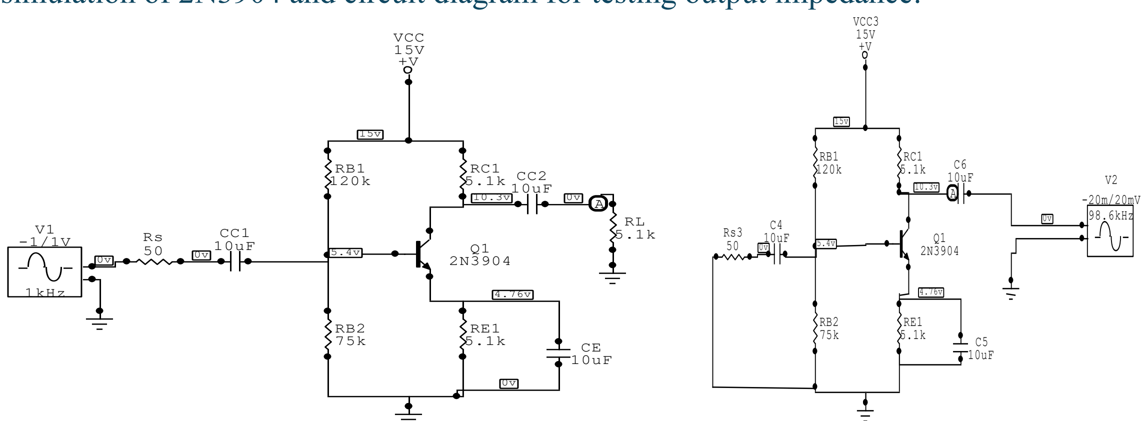
Appendix 1: Part I c): bias circuit i) , bias circuit ii) and bias circuit iii)



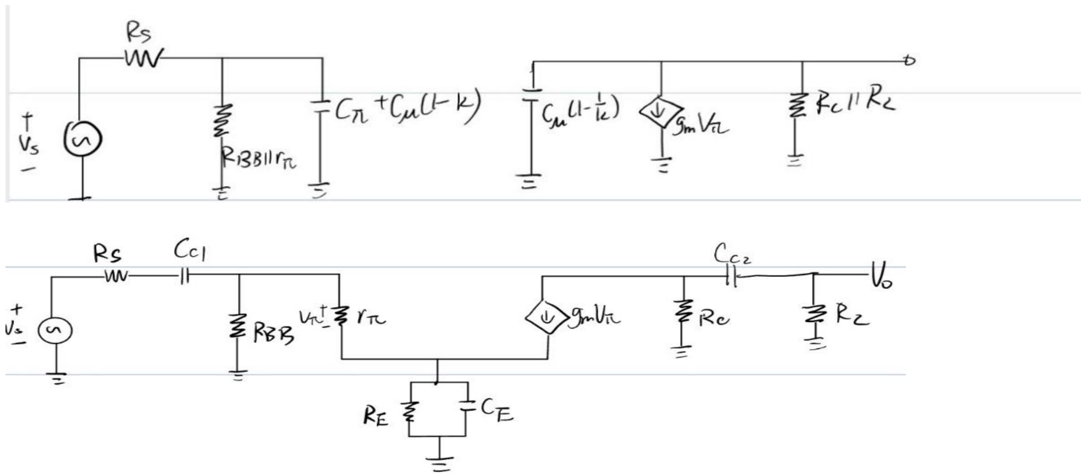
Appendix 2 bias circuit: Bias circuit for 2N3904 and 2N4401



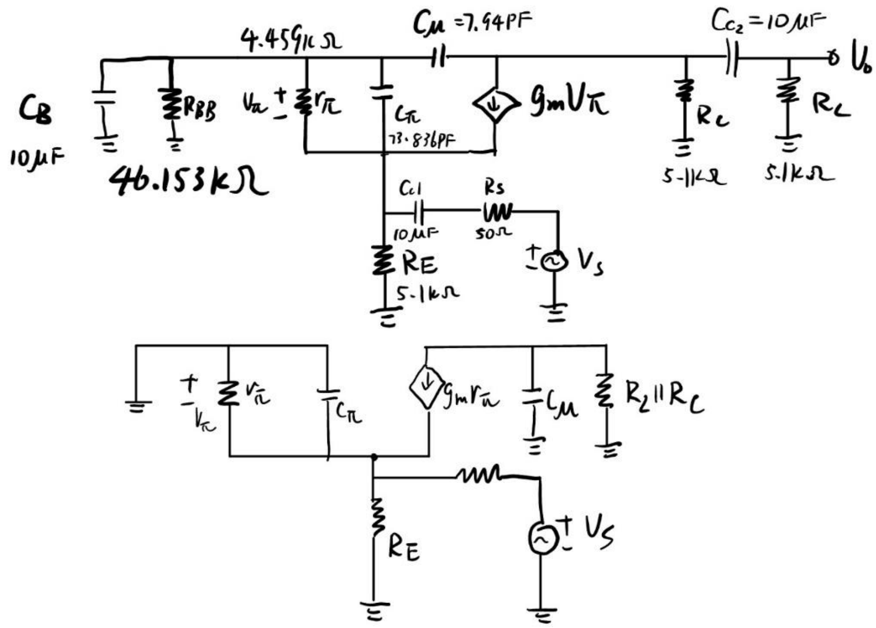
Appendix 3 Part II a) Circuit simulation of 2N3904 and circuit diagram for testing output impedance:



Appendix 4 part II a) High-frequency and low-frequency small-signal model:



Appendix 5 part III a) Small signal circuit and High frequency model :



Appendix 6. Circuit for input impedance and output impedance.