Mini Project 2

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Part 1

A Values of small signal parameters h_{fe}, h_{ie}, and h_{oe} for V_{CE} = 10V, I_c = 1mA, f = 1kHz, and T = 25 °C for a 2222N2A NPN transistor

Parameter (Units)	Minimum Value	Maximum Value
h_{fe}	50	300
h_{ie} (kΩ)	2.0	8.0
h_{oe} (μ℧)	5.0	35

Values found from:

https://alltransistors.com/pdfview.php?doc=mtp2n2222a_p2n2222a.pdf&dire=_motorola

B Plot Vbe vs Ib, Vce vs Ic with characteristic Ib, and Vce vs Ic with characteristic Vbe graphs, calculate β, gm, rπ, ro, and Early Voltage (Va)

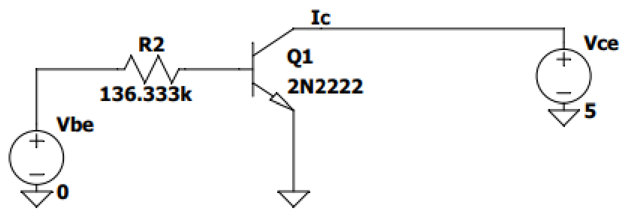


Figure 1.1. Circuit used to calculate Ib vs Vbe graph

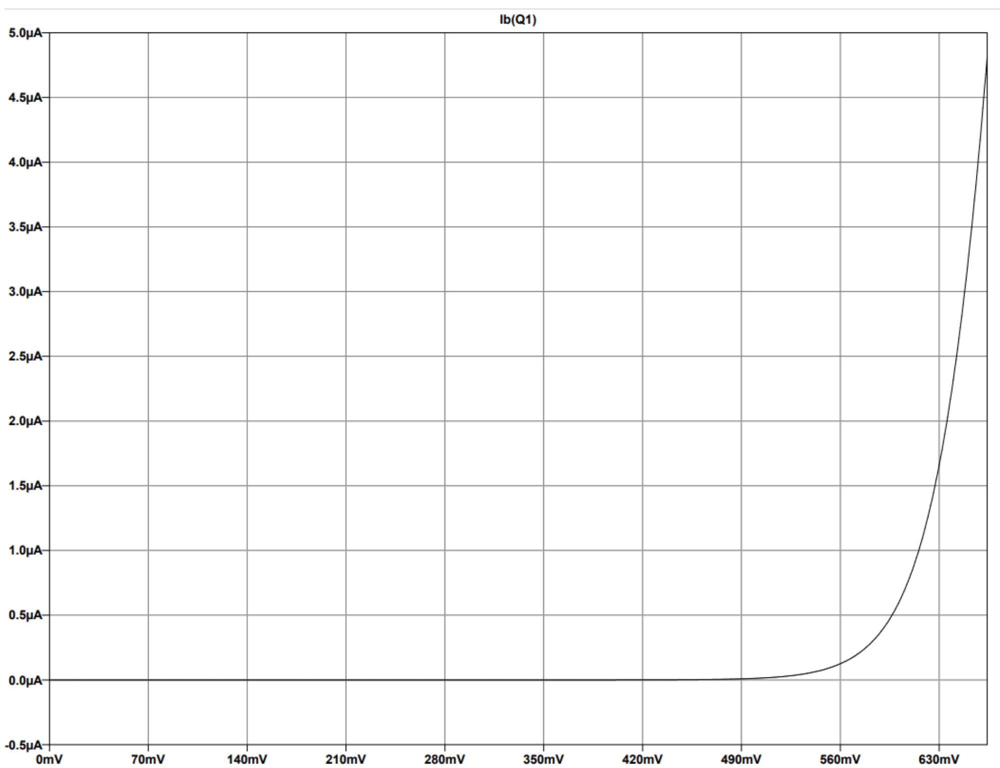


Figure 1.2. Resultant Ib vs Vbe relationship

I used the circuit in the previous part to measure the current going into the Base of the NPN amplifier. I adjusted the Vce and Vbe elements to measure the remaining relationships shown in the next pages.

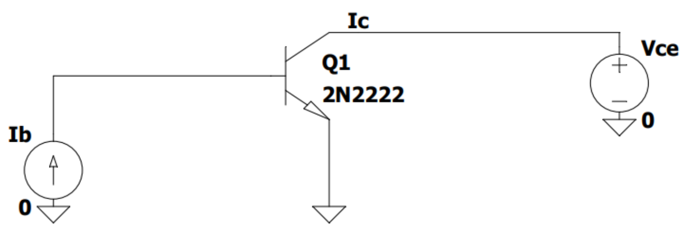


Figure 1.3. Circuit used to calculate Ic vs Vce graph with characteristic Ib

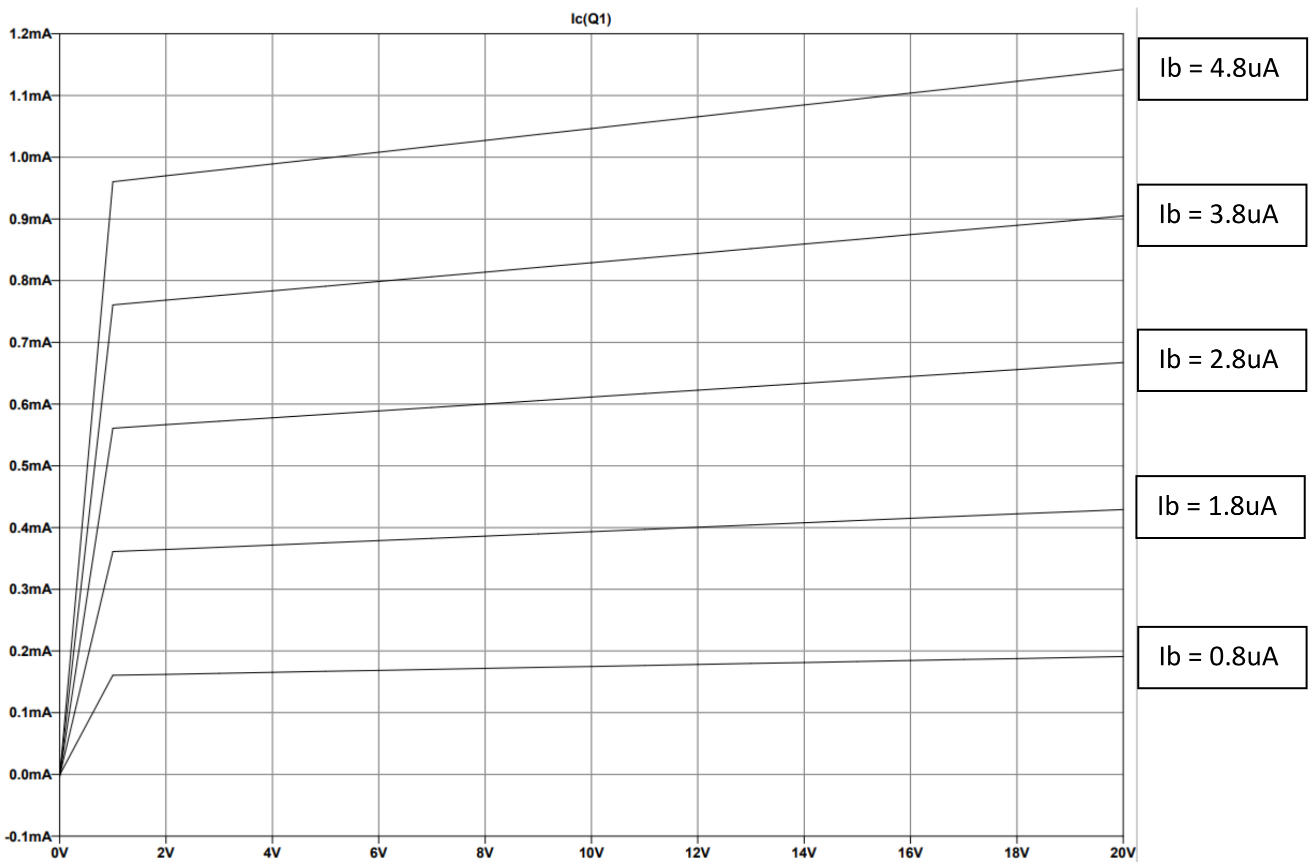


Figure 1.4. Resultant Ic vs Vce relationship with characteristic Ib

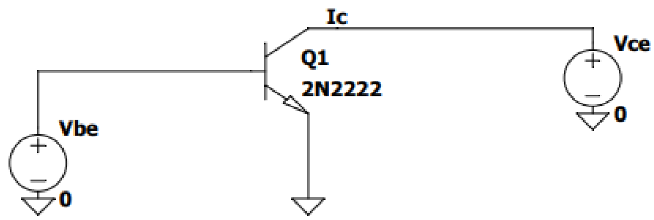


Figure 1.5. Circuit used to calculate Ic vs Vce graph with characteristic Vbe

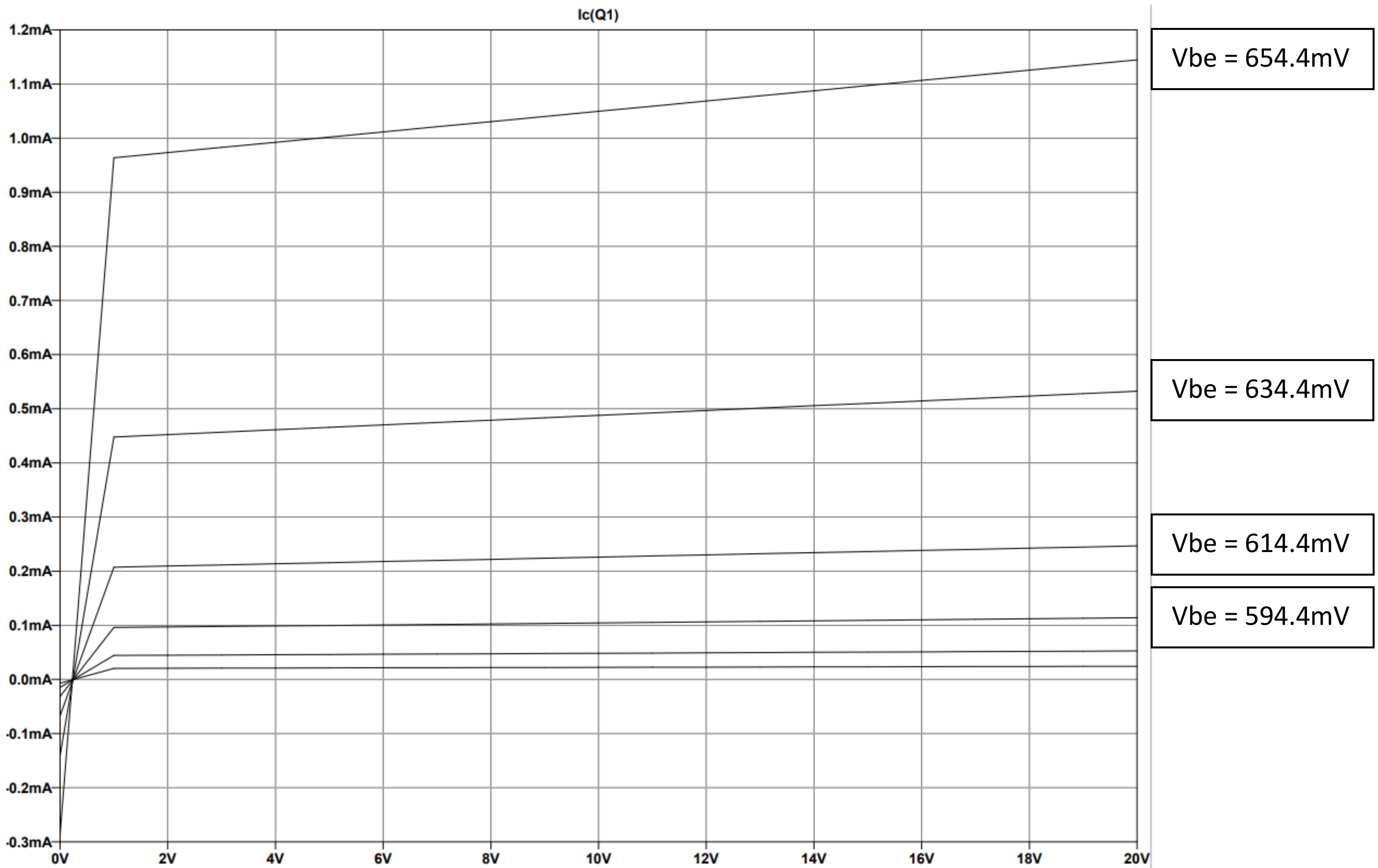


Figure 1.6. Resultant Ic vs Vce relationship with characteristic Vbe

We want the operating Ic = 1mA at Vce = 5V. We see that this operating point occurs at Ib = 4.8µA and Vbe = 654.4 mV.

$\beta = \frac{Ic}{Ib} = \frac{1mA}{4.8\mu A}$ **= 210.526** $\quad$ $gm = \frac{Ic}{VT} = \frac{1mA}{25mV}$ **= 0.04℧** $\quad$ $r\pi = \frac{\beta}{gm} = \frac{210.256}{0.04℧}$ **= 5.26kΩ**

To find Va, I needed to find where the Ic vs Vce graph intersects with the x-axis.

y = mx+ b   m = $\frac{1.05mA-1mA}{10V-5V}$ = 10m℧

b = y – mx = 1.05mA – 10µ(10) = 0.95 mA

Ic = 10m℧ * Vce + 0.95mA → Ic = 0 → 10m℧ * Vce = -0.95 → Vce = -95 = -Va

Therefore, **Va = 95V**

ro = $\frac{Va}{Ic}$ = $\frac{95V}{1mA}$ = 95kΩ

h_{fe} is equivalent to β. Since β is within the range of 50 to 300 it is a good calculation

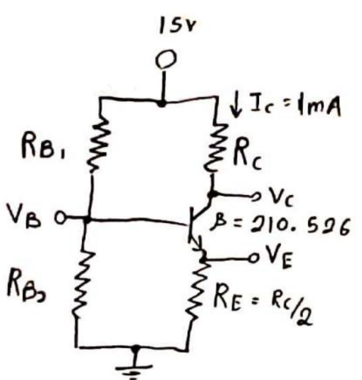
h_{ie} is equivalent to rπ. Since rπ is within the range of 2.0k to 8.0k it is a pretty good calculation.

h_{oe} is equivalent to ro^{-1}. Since ro is within the range of $5.0\mu^{-1}$ and $35\mu^{-1}$ it is a good calculation.

C

i) Forward bias the NPN for Vce <= 4V in bias network. Calculate all resistors values and DC Operating pt

First, I started by trying to find Rc and Re by using some basic NPN relations and KCL equations, as well as parameters from the previous part



① $V_{CE} = V_C - V_E = 4V$

② $\frac{15 - V_C}{R_C} = 1\,mA$

③ $I_E = \alpha I_C \rightarrow \frac{V_E}{R_C/2} = \frac{\beta+1}{\beta} \cdot 1mA$

Solving this

$\boxed{R_C = 7.322\,k\Omega}$

$\boxed{R_E = 3.661\,k\Omega}$

I set RB1 = 50k, I used trial and error until I found an RB2 that brought Ic = 1mA, its operating point. RB2 = 20.8k. This is the resultant circuit

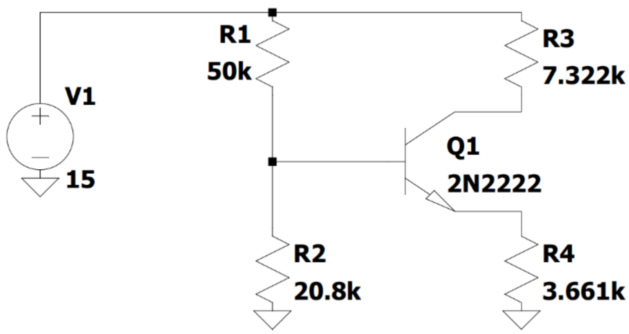


Figure 1.7. Bias network circuit built using calculated resistor values

I analyze the circuit and find the DC operating point.

Ic = 1mA **Ie = 1.001mA** **Ib = 4.86µA** **Vbe = 0.7V** **Vce = 3.99V**

ii) Use 1/3rd rule to bias the circuit

Below is my work for the 1/3rd rule to calculate RB1, RB2, Re, and Rc. I used these resistors to value the network below

$V_C = \frac{2}{3}(15V) = 10V$ $V_E = \frac{1}{3}(15V) = 5V$ $\beta = 210.526$ $I_C = 1mA$ $I_E \approx I_E = 1mA$

$V_{BE} \approx 0.7V$ $I_B = I_C/\beta = \frac{1mA}{210.526} = 4.75mA$

$$\boxed{R_{B_1} = \frac{\frac{2}{3}(15V) - 0.7V}{1mA/\sqrt{\beta}} = 1.349 \cdot 10^5 \Omega}$$

$$\boxed{R_{B_2} = \frac{\frac{1}{3}(15V) - 0.7V}{I_E\left(\frac{1}{\sqrt{\beta}} - \frac{1}{\beta+1}\right)} = 8.88 \cdot 10^4 \Omega}$$

$$\boxed{R_C = \frac{15 - V_C}{I_C} = 5k}$$

$$\boxed{R_E = \frac{5 - 0}{I_E} = 5k}$$

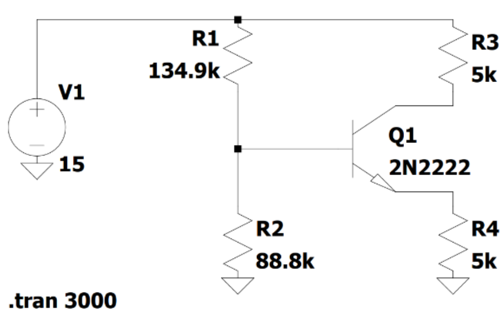


Figure 1.8. Bias network circuit using 1/3rd rule

I analyze the circuit and find the DC operating point.

Ic = 1.003mA **Ie = 1.008mA** **Ib = 4.827µA** **Vbe = 0.7V** **Vce = 4.969V**

iii) Use commonly available resistors to replace the resistors found using the 1/3rd rule

Below is the transformed version of Figure 1.8 with commonly available resistors

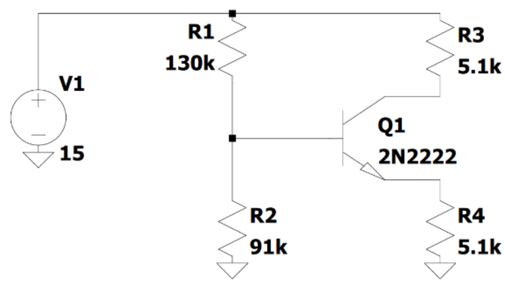


Figure 1.9. Bias network circuit using 1/3rd rule and commonly available resistors

I analyzed the circuit and find the DC Operating point.

Ic = 1.026mA   Ie = 1.031mA   Ib = 4.954µA   Vbe = 0.7V   Vce = 4.513V

iv) Comment on the DC operating points between the different circuits in i – iii

By comparing the 3 DC operating points, I notice that Ic consistently is around 0.1mA, likewise Ie is also always around 0.1mA. Ib is also very close together and Vbe are very close as well. Vce are a little bit different, where Vce in the circuit in part i is close to 4V whereas the circuits in parts ii – iii were closer to 5V, however, the circuit in part iii is closer to the original circuit than part i was.

Based on these observations I can conclude that the 1/3rd rule is accurate enough for our purposes and adjusting resistor values to commonly available resistors did not affect the accuracy of our operating points.

<u>**D**</u> Using the circuit in Part C iii, find DC operating points with the 2N3904 transistor and 2N4401 transistor.

I used the same circuit as Part C iii and simply changed the transistors between operating points.

2N3904 NPN DC Operating Points:

Ic = 1.022mA   Ie = 1.025mA   Ib = 3.279µA   Vbe = 0.7V   Vce = 4.768V

2N4401 NPN DC Operating Points:

Ic = 1.022mA   Ie = 1.025mA   Ib = 3.279µA   Vbe = 0.7V   Vce = 4.768V

Comparing the 3 operating points, Ic is very similar, and Ie is also quite similar. Ib of 2N2222A is quite different compared to the other 2 transistors. Vbe is similar and Vce is also quite similar, on Ib is different.

Also, interestingly, the DC Operating points of 2N3904 and 2N4401 are equivalent.

Part 2

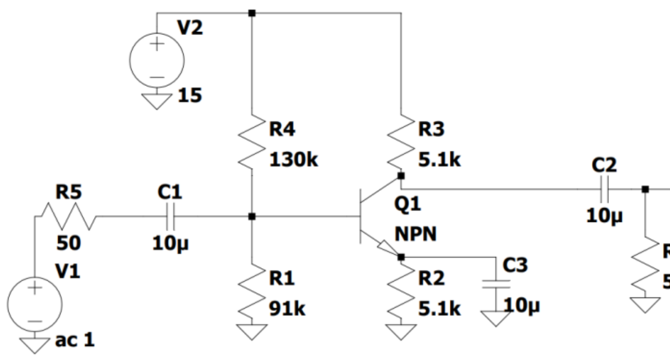


Figure 2.1. Common Emitter Amplifier

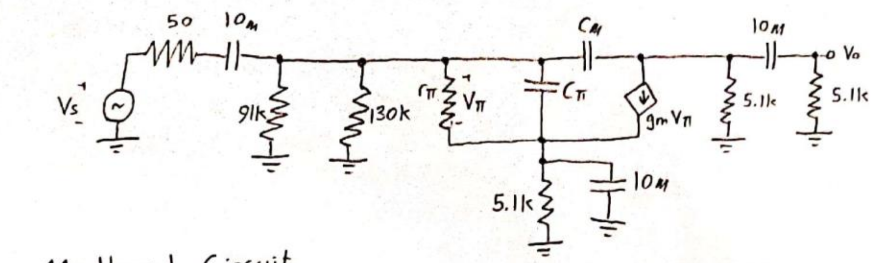
The RLoad (R6 in this model) was chosen by trial and error. I tried multiple load resistors and found that the output power (V*I) was highest when RLoad = Rc = Re = 5.1k.

<u>**A**</u> Calculate poles and zeroes of this circuit and then measure them. Do this for all NPNs (2N2222A, 2N3904, 2N4401)

Showing the work for all 3 transistors would take a lot of space, so I will show the general working using symbols and use the same method for all the poles and zeroes for each transistor.

2

Hybrid-π Model



$\beta = I_C / I_B$

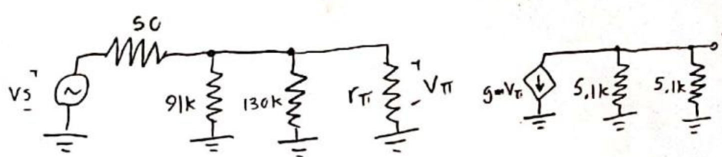
$g_m = I_C / V_T$

$r_\pi = \beta / g_m$

$C_\pi = 2 \cdot CJE + TF \cdot g_m \approx 10^{-12} F$

$C_\mu = \dfrac{CJC}{\left(1 + \frac{V_{CB}}{VJC}\right)^{MJC}} \approx 10^{-12} F$

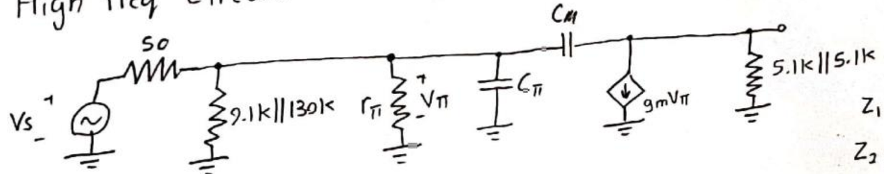
Midband Circuit



$\dfrac{V_\pi}{V_s} = \dfrac{r_\pi}{50 + 91k \| 130k \| r_\pi}$, $\dfrac{V_o}{V_\pi} = -g_m(5.1k \| 5.1k)$

$A_m = \dfrac{V_o}{V_s} = \dfrac{V_\pi}{V_s} \cdot \dfrac{V_o}{V_\pi}$

High freq Circuit

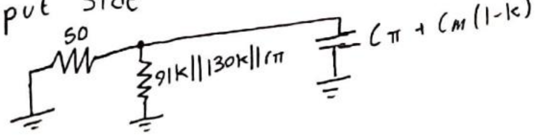


$K = -g_m(5.1k \| 5.1k)$

$Z_1 = Z \dfrac{1}{1-K} \rightarrow \dfrac{1}{C_1 s} = \dfrac{1}{C_\mu s} \cdot \dfrac{1}{1-K} \rightarrow C_1 = C_\mu(1-K)$

$Z_2 = Z \dfrac{K}{K-1} \rightarrow C_2 = C_\mu$

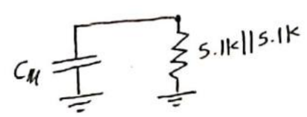
Input Side



$$\boxed{\omega_{HP1} = \frac{1}{(C_\pi + C_\mu(1-K))(91k \| 130k \| r_\pi)}}$$

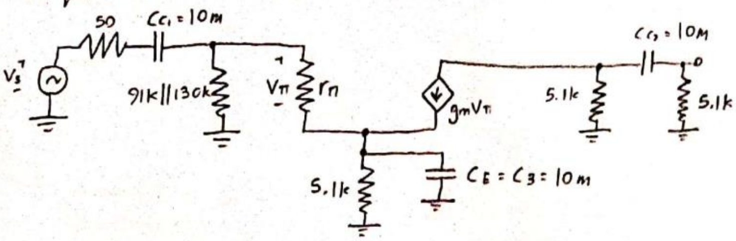
Output side

$$\boxed{\omega_{HP2} = \frac{1}{C_\mu(5.1k \| 5.1k)}}$$



2.

Low freq Circuit



$$\boxed{\omega_{LZ_1} = \omega_{LZ_2} = 0}$$

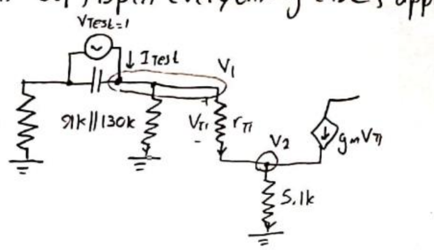
3rd zero @ $Z_E = \infty$ or $Y_E = 0$

$$Y_E = \frac{1}{5.1k} + sC_E = 0$$

$$s = -\frac{1}{5.1k \cdot C_E} \rightarrow \boxed{\omega_{LZ_3} = \frac{1}{10m \cdot 5.1k}}$$

Because of where C_{C_1} is, we choose it so it will short before other capacitors, or else it would act like a low-pass circuit @ low freq. From C_{C_1}'s point of view, the other caps are OCs.

- Focus on C_{C_1}, open everything else, apply a test voltage instead of C_{C_1} to find R @ C_{C_1}



$$I_{Test} = \frac{V_1}{91k||130k} + \frac{V_1 - V_2}{r_\pi}$$

$$g_m(V_1 - V_2) + \frac{V_1 - V_2}{r_\pi} = \frac{V_2}{5.1k}$$

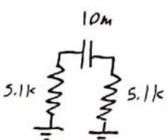
$$I_{Test} = \frac{1 - V_1}{50}$$

$$R_{eq} = \frac{V_{Test}}{I_{Test}} = \frac{1}{I_{Test}}$$

SOLVE

$$\boxed{\omega_{LP_1} = \frac{1}{10m \cdot R_{eq}}}$$

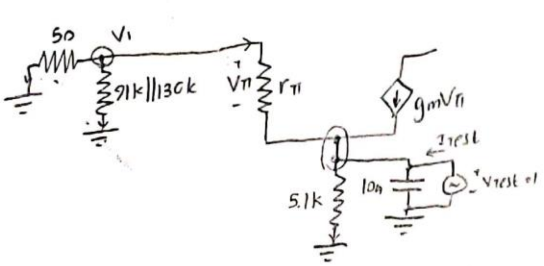
- Focus on C_{C_2}, it exists at output so we ignore rest of the circuit



$$\boxed{\omega_{LP_2} = \frac{1}{10m\,(5.1k||5.1k)} = 9.804\ \text{Hz}}$$

- Focus on C_E (we will also call C_3 so pole numbering is consistent) - SC every other capacitor

Apply VTest to get equivalent R across C_E



$$\frac{V_1}{50} + \frac{V_1}{91k||130k} = \frac{V_1 - 1}{r_\pi}$$

$$I_{Test} + g_m V_\pi + \frac{V_1 - 1}{r_\pi} = \frac{1}{5.1k}$$

$$V_\pi = V_1 - V_2$$

$$R_{eq} = \frac{1}{I_{Test}}$$

Solve

$$\boxed{\omega_{LP_3} = \frac{1}{10m \cdot R_{eq}}}$$

Analyzing 2N2222A

gm = 0.04℧ rπ = 5.26kΩ Cπ = 40.411pF Cμ = 8.349pF

Am = -111 w_{Hp1} = 20.74MHz w_{Hp2} = 201.3MHz w_{Lz1} = w_{Lz2} = 0

w_{Lz3} = 19.608Hz w_{Lp1} = 1.932Hz w_{Lp2} = 9.804Hz w_{Lp3} = 4.006kHz

Output bode plot from simulated circuit

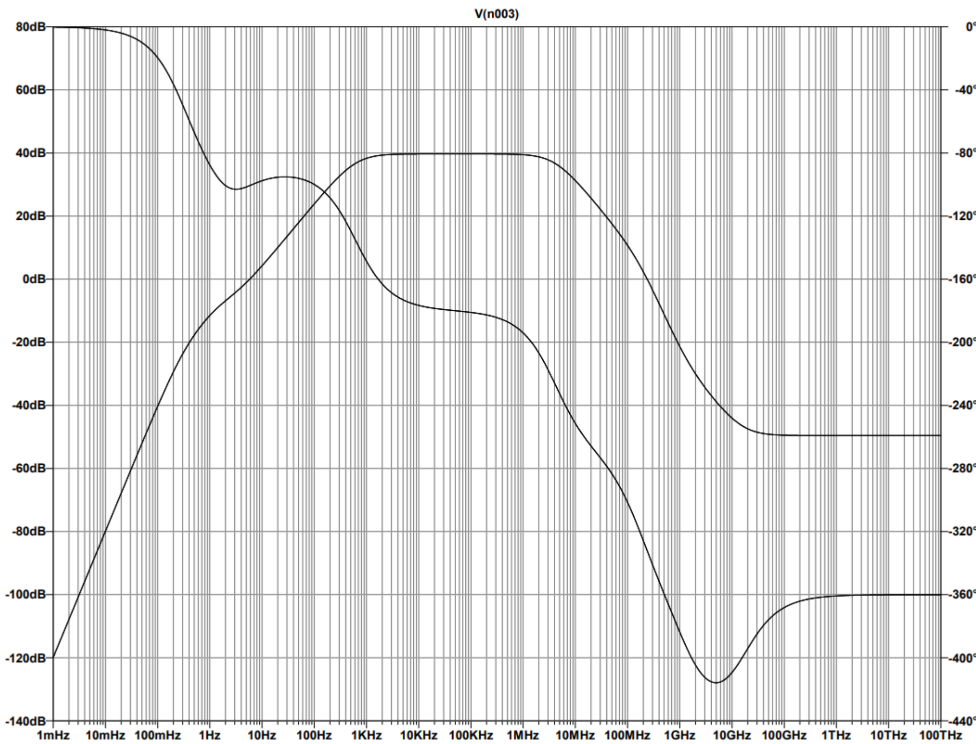


Figure 2.2. 2N2222A CE amplifier bode plot

To measure poles from the simulated circuit, I used linear approximation

These are the comparisons between the calculated and measured (approximate) locations of poles and zeroes

	w_{Lp1}	w_{Lp2}	w_{Lp3}	w_{Lz1}	w_{Lz2}	w_{Lz3}	w_{Hp1}	w_{Hp2}	w_{Hz1}	w_{Hz2}
Calculated	1.959	9.804	4.001E3	0	0	19.608	2.074E7	2.013E8	DNE	DNE
Measured	1.30	6.50	3.80E3	0	0	11.0	1.20E7	7.2E8	6.5E9	1.2E10

Analyzing 2N3904

$gm = 0.04℧$ $r\pi = 7.43k\Omega$ $C\pi = 25pF$ $C\mu = 1.948pF$

$Am = -105.3$ $w_{Hp1} = 22.45MHz$ $w_{Hp2} = 201.3MHz$ $w_{Lz1} = w_{Lz2} = 0$

$w_{Lz3} = 19.608Hz$ $w_{Lp1} = 1.932Hz$ $w_{Lp2} = 9.804Hz$ $w_{Lp3} = 4.006kHz$

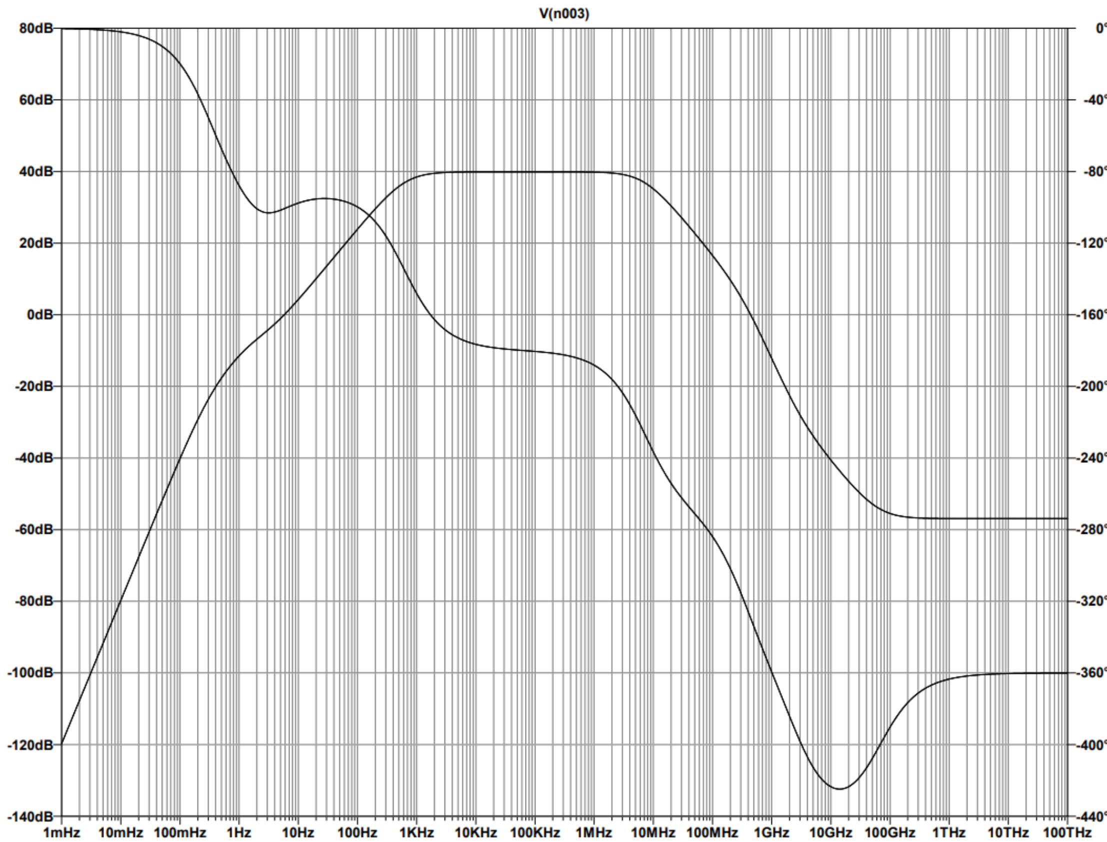


Figure 2.3. 2N3904 CE amplifier bode plot

	w_{Lp1}	w_{Lp2}	w_{Lp3}	w_{Lz1}	w_{Lz2}	w_{Lz3}	w_{Hp1}	w_{Hp2}	w_{Hz1}	w_{Hz2}
Calculated	1.932	9.804	4.006E3	0	0	19.608	2.254E7	2.013E8	DNE	DNE
Measured	1.350	7.890	4.10E3	0	0	16.50	3.4E7	4.2E8	4.3E10	8.9E10

Analyzing 2N4401

$gm = 0.04℧$ $r\pi = 3.01k\Omega$ $C\pi = 0.6712pF$ $C\mu = 5.470pF$

$Am = -105.1$ $w_{Hp1} = 22.45MHz$ $w_{Hp2} = 71.70MHz$ $w_{Lz1} = w_{Lz2} = 0$

$w_{Lz3} = 19.608Hz$ $w_{Lp1} = 2.028Hz$ $w_{Lp2} = 9.804Hz$ $w_{Lp3} = 3.957kHz$

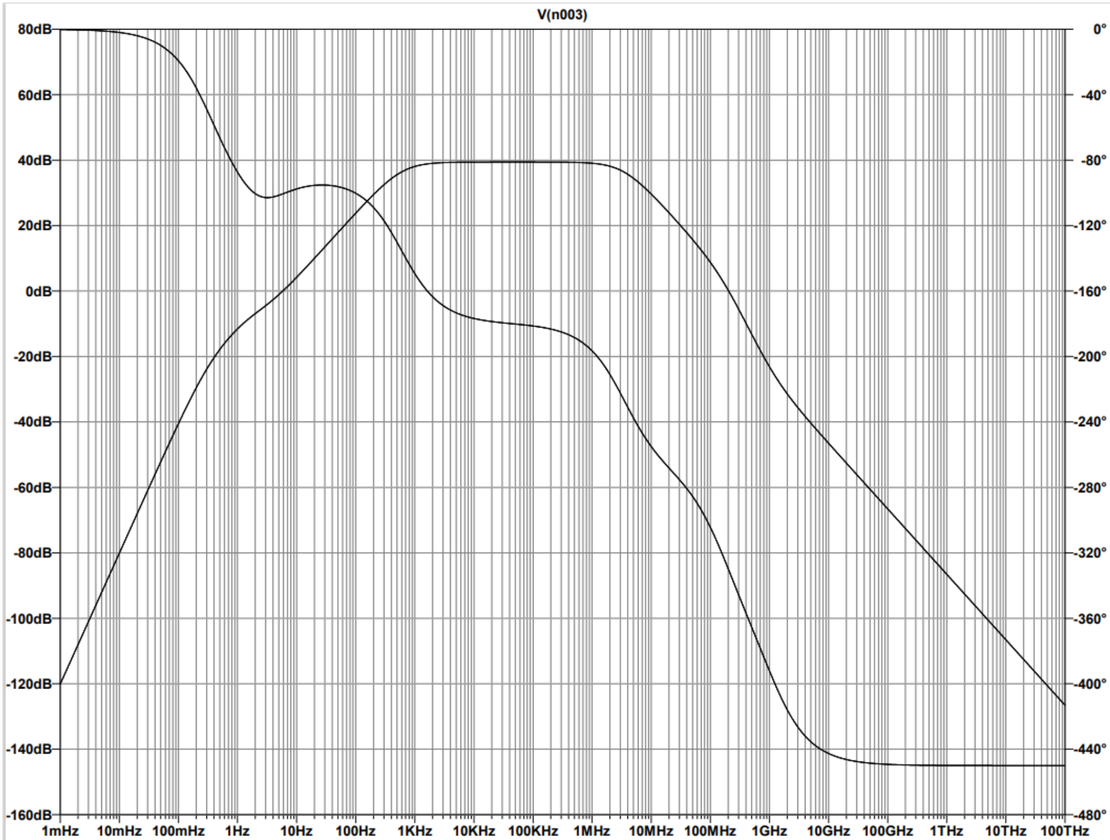


Figure 2.4. 2N4401 CE amplifier bode plot

	w_{Lp1}	w_{Lp2}	w_{Lp3}	w_{Lz1}	w_{Lz2}	w_{Lz3}	w_{Hp1}	w_{Hp2}	w_{Hz1}	w_{Hz2}
Calculated	2.028	9.804	3.957E3	0	0	19.608	2.254E7	7.170E7	DNE	DNE
Measured	1.350	6.890	2.1E3	0	0	16.50	3.4E7	4.2E7	4.3E10	8.9E10

B Change input voltage amplitude until the Vo/Vs trend is no longer linear, set a midband frequency

I observe that from the 2N2222A transistor, my midband occurs from a little less than 10kHz and around 10MHz. I set my focus frequency to 10kHz.

Through my circuit simulation software, I measured the amplitude of the output (Vo) and constantly changed my input (Vs). I plotted the values on Excel and plotted the trend

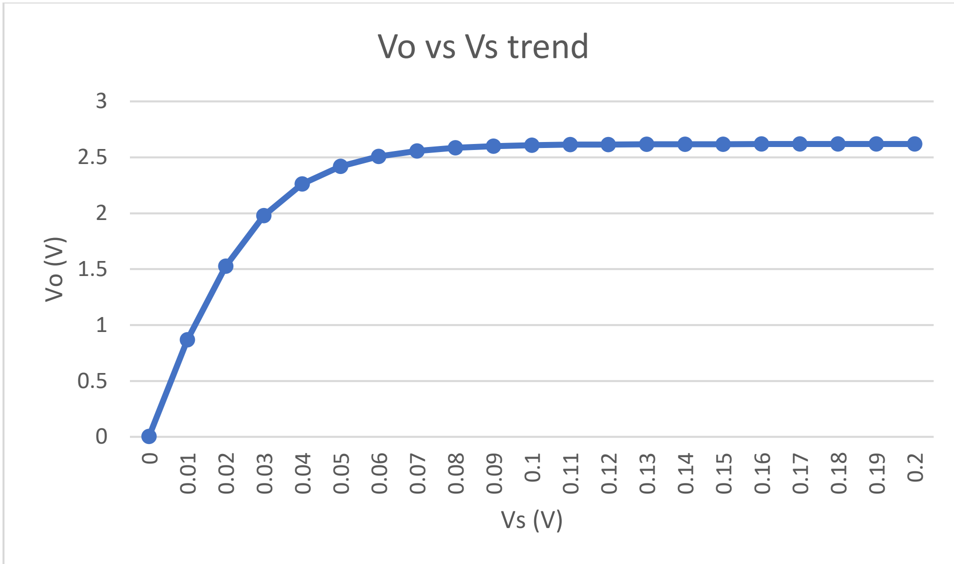
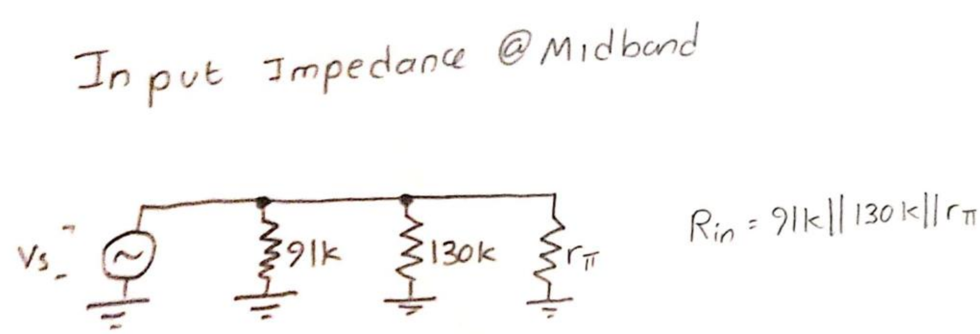


Figure 2.5. Vo vs Vs trend

Looking at the graph, it looks like it stops being linear when Vs = 15mV

<u>C</u> Measuring input impedance, take out 50-ohm resistor

This is how I will calculate input impedance for the circuit at midband.



To measure input impedance, I will input Vs = 15mV (Vin), and measure the amplitude of the current going through the Vs (Iin). Then through Ampere's Law, Rin = Vin / Iin

2N222A

Calculated: rπ = 5.26k Rin = 4.789k

Measured: Rin = (15mV/4.645mA)-50 = 6.526k

2N3904

Calculated: $r\pi$ = 7.432k Rin = 6.256k

Measured: Rin = (15mV/1.886mA)-50 = 67.903k

2N222A

Calculated: $r\pi$ = 3.04k Rin = 2.853k

Measured: Rin = (15mV/3.665mA)-50 = 4.043k

D Measuring output impedance, include 50-ohm resistor

I manually set the load resistance to be equal to 5.1k, so the calculated Rout = 5.1k

To measure output impedance, I will input Vs = 15mV, and measure Vo (Vo), and measure the amplitude of the current going through the Vo (Io). Then through Ampere's Law, Ro = Vo / Io

2N222A

Calculated: Rout = 5.1k

Measured: Rin = (1.223V/0.2399mA) = 5.1k

2N3904

Calculated: Rout = 5.1k

Measured: Rin = (1.250V/0.2452mA) = 5.1k

2N222A

Calculated: Rout = 5.1k

Measured: Rin = (1.184V/0.2321mA) = 5.1k

Interestingly, the Routs of each NPN is the same and exactly what my calculated Rout is

<u>E</u> Which transistor gives the best performance

For performance, I would choose the 2N3904 transistor. The reason I would choose this is because it has the largest midband frequency range. This indicates that the CE Amplifier will work for a larger range of frequencies, making it a much more versatile amplifier, although the difference in range isn't that great compared to other amplifiers so any of the transistors are viable choices.