Mini Project 3

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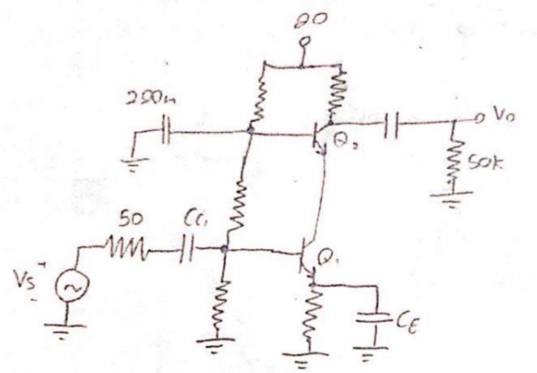
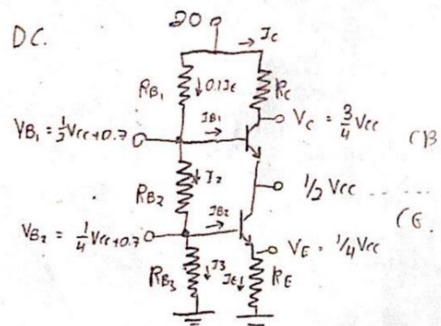
Part 1

I found that the β for a 2N3904 transistor ranges between 100-300, I will set β = 300 for my calculations for both transistors.

I used the 1/4th rule to figure out the resistor values, at DC analysis, the capacitors act like open circuits. I witnessed in MP2 that the load resistance is equivalent to Rc, so I set Rc to be around 2.5k since that is the required Rout, and the closest common resistor value is 2.4k, therefore, Rc = 2.4kΩ.



$\beta = 100, \quad V_T = 25mV$



$V_C = \frac{3}{4}(20) = 15\,V$

$V_E = \frac{1}{4}(20) = 5\,V$

$V_{B_1} = \frac{1}{2}(20) + 0.7 = 10.7\,V$

$V_{B_2} = \frac{1}{4}(20) + 0.7 = 5.7\,V$

$\boxed{R_L = R_C \approx 2.4k}$

$I_{C_1} = \frac{20-15}{2.4k} = 2.083\,mA$

$R_E = \frac{5-0}{I_E} \Rightarrow \boxed{R_E = 2.4k}$

$I_{E_1} \cong I_{C_2} \cong I_{E_2} = 2.083mA$

$I_1 = 0.1 I_E = 0.2083\,mA$

$I_{B_1} = I_{C_1}/\beta = 20.83mA$

$R_{B_1} = \frac{20-10.7}{I_1} \Rightarrow \boxed{R_{B_1} = 44.647k}$

$I_2 = I_1 - I_{B_1} = 187.47\,mA$

$R_{B_2} = \frac{10.7-5.7}{I_2} \Rightarrow \boxed{R_{B_2} = 26.671k}$

$I_{B_2} = I_{C_2}/\beta = 20.83mA$

$I_3 = I_2 - I_{B_2} = 166.64mA$

$R_{B_3} = \frac{5.7-0}{I_3} \Rightarrow \boxed{R_{B_3} = 34.205k}$

<u>A</u> DC Operating points

I_{b1} = 7.429µA **I_{c1} = 2.289mA** **I_{e1} = -2.296mA** **V_{be1} = 0.676V** **V_{ce1} = 3.94V**

I_{b2} = 7.375μA **I_{c2} = 2.296mA** **I_{e2} = 2.304mA** **V_{be2} = 0.676V** **V_{ce2} = 5.035V**

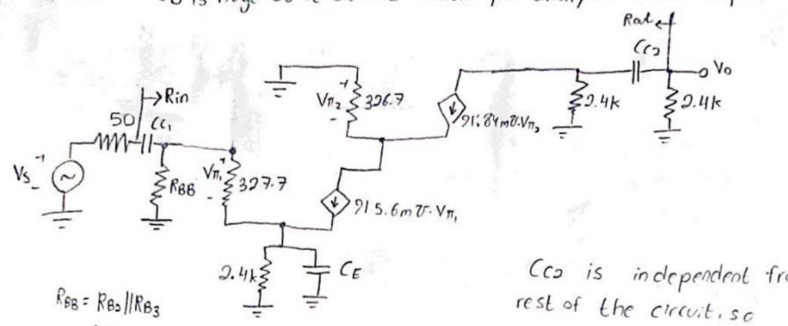
Now that I have a value for Ic, I will use these values to find gm and rπ. I assumed VT = 25mV

$g_{m1} = Ic_1/VT = 91.56m℧$ **$r_{\pi 1} = \beta/g_{m1} = 327.7\Omega$**

$g_{m2} = Ic_2/VT = 91.84m℧$ **$r_{\pi 2} = \beta/g_{m2} = 326.7\Omega$**

This is my work to find capacitance values

Low f: CB is huge so it shorts when you analyze other caps

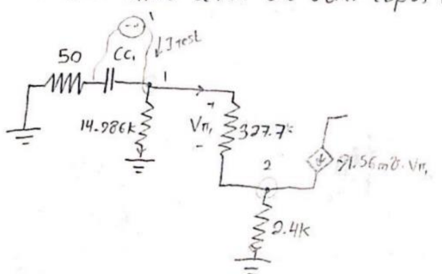


$R_{BB} = R_{B2} \| R_{B3}$
$= 14.986k$

Cc2 is independent from the rest of the circuit, so

$$\omega_{p\,Cc2} = \frac{1}{(2.4k + 2.4k)\,C_{c2}}$$

Cc1 will short before the other caps, do OC test on Cc1



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

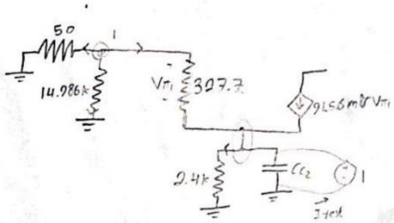
$$I_{test} = \frac{V_1}{14.986k} + \frac{V_1 - V_2}{327.7}$$

$$\frac{V_1 - V_2}{327.7} + 91.56m℧ = \frac{V_2}{2.4k}$$

$$R_{Cc1} = \frac{1}{I_{test}} = 10.522k$$

$$\omega_{L\,p\,Cc1} = \frac{1}{10.522k \cdot C_{c1}}$$

Do SC test on CE



$$\frac{V_1}{50} + \frac{V_1}{14.986k} + \frac{V_1 - 1}{327.7} = 0$$

$$91.56m℧ \cdot (V_1 - 1) + \frac{V_1 - 1}{327.7} + I_{test} = \frac{1}{2.4k}$$

$$R_{CE} = \frac{1}{I_{test}} = 10.10$$

$$\omega_{L\,p\,CE} = \frac{1}{10.10 \cdot C_E}, \quad \omega_{LZ\,CE} = \frac{1}{2.4k \cdot C_E}$$

CE sees the smallest R, so it will have the dominant pole. Use that pole to find the CE.

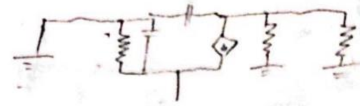
$$500 \cdot 2\pi = \frac{1}{10.10 \cdot C_E} \rightarrow C_E = \frac{1}{10.10 \cdot 500 \cdot 2\pi} = 26.263\mu F \rightarrow \text{closest cap} \rightarrow \boxed{C_E = 22\mu F}$$

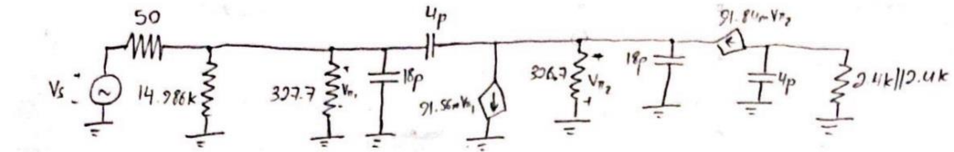
For economic sake I'll set $\boxed{C_{c1} = C_{c2} = C_E = 22\mu F}$

$$\omega_{3dB} = \sqrt{\omega_{Lp\,Cc1}^2 + \omega_{Lp\,Cc2}^2 + \omega_{Lp\,CE}^2 - 2\omega_{LZ\,CE}^2} = 3.751k \text{ rad/s} \rightarrow \boxed{f_{Lp3dB} = 596.88 \text{ Hz}}$$

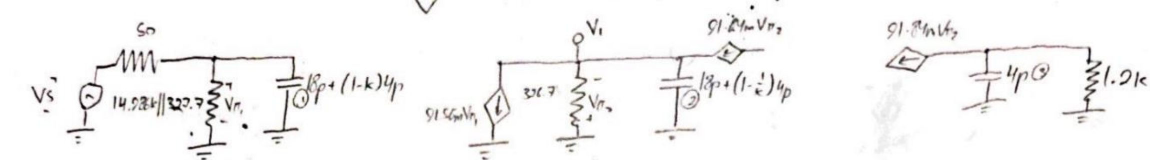
B Compare w_{L3dB} values

High freq: From datasheet $C_\pi = 18pF$, $C_m = 4pF$





Get 3 circuits



Get k: KCL around V_1

$$91.56m V_{\pi_1} + \frac{V_1}{326.7} = 91.84m V_{\pi_2} \, , \quad V_{\pi_2} = -V_1$$

$$91.56m V_{\pi_1} = -V_1\left(\frac{1}{326.7} + 91.84m\right)$$

$$k = \frac{V_1}{V_\pi} = -\frac{91.56m}{91.84m} \approx -1$$

$$\omega_{Hp_1} = \left[(18p + 2(4p)) \cdot 50 \| 14.986k \| 327.7\right]^{-1} = \boxed{8.892 \cdot 10^8 \text{ rad/s} = \omega_{Hp_1}}$$

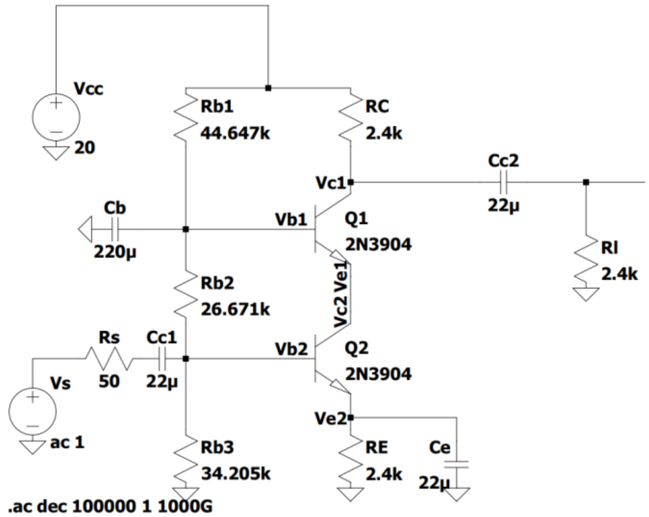
$$\omega_{Hp_3} = \left[4p \cdot 1.2k\right]^{-1} = \boxed{2.083 \cdot 10^8 \text{ rad/s} = \omega_{Hp_3}}$$

$$\omega_{Hp_2} = \left[\frac{r_\pi}{1+\beta}(18p + 2(4p))\right]^{-1} = \boxed{3.544 \cdot 10^{10} \text{ rad/s} = \omega_{Hp_2}}$$

$$\omega_{Hp3dB} = \sqrt{\frac{1}{\omega_{Hp_1}^2} + \frac{1}{\omega_{Hp_2}^2} + \frac{1}{\omega_{Hp_3}^2}}^{\,-1} = \boxed{2.028 \cdot 10^8 \text{ rad/s} = \omega_{Hp3dB}}$$

$$\boxed{f_{Lp3dB} = 3.228 \cdot 10^7 \text{ Hz}}$$

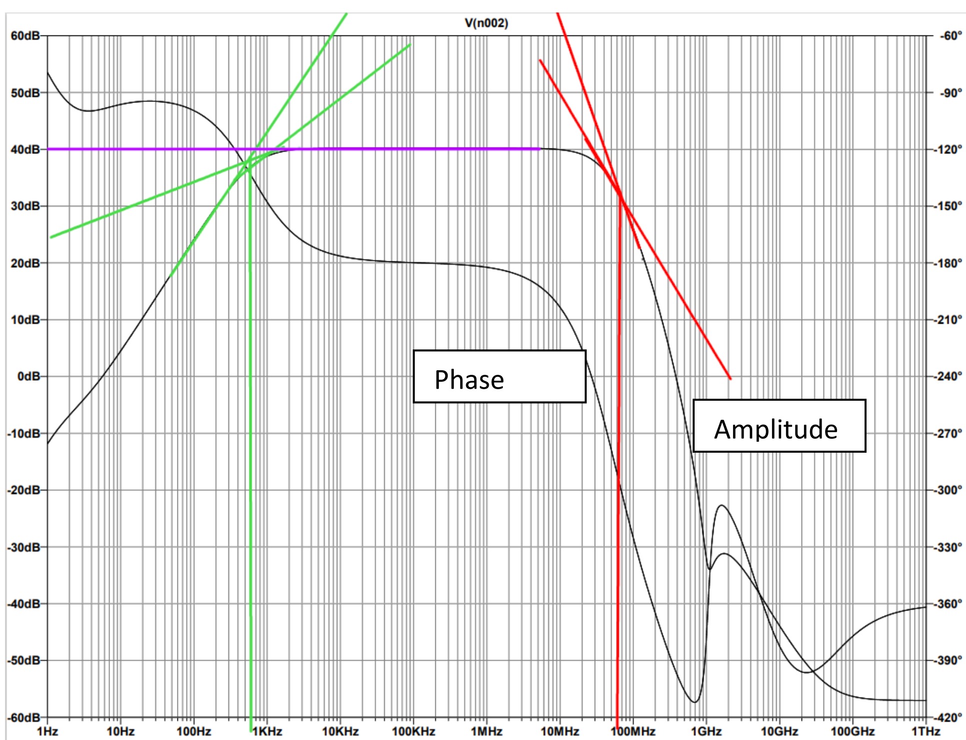
This is my final circuit:



I calculated my w_{Lp3dB} as 3.751k rad/s → f_{Lp3dB} = 596.88Hz

I calculated my w_{Hp3dB} as 202.8 Mrad/s → f_{Hp3dB} = 32.28 MHz

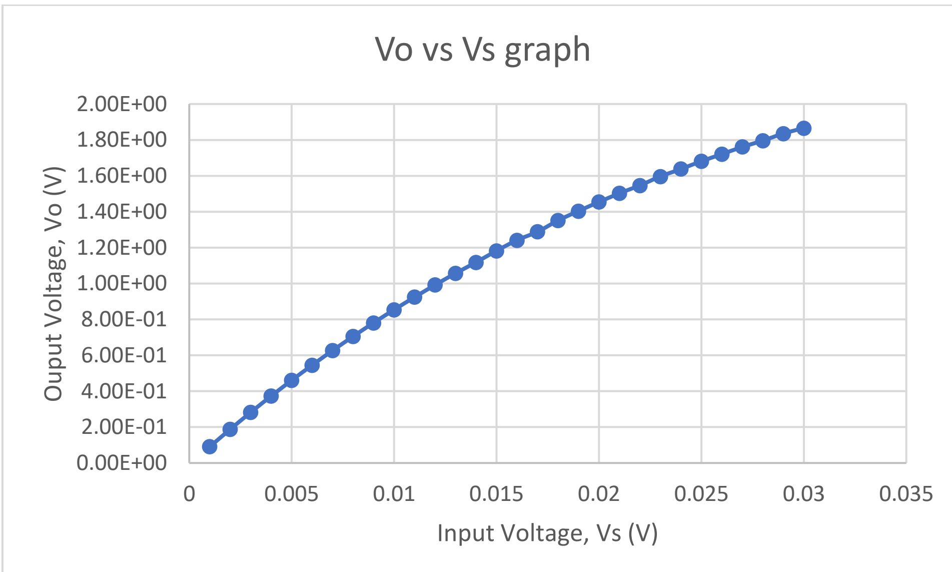
By taking the transfer function and using the linear approximation method shown below using Gimp: I get my f_{Lp3dB} = ~600 and f_{Hp3dB} = ~45M. These values do have a lot of error with the method I use, however.



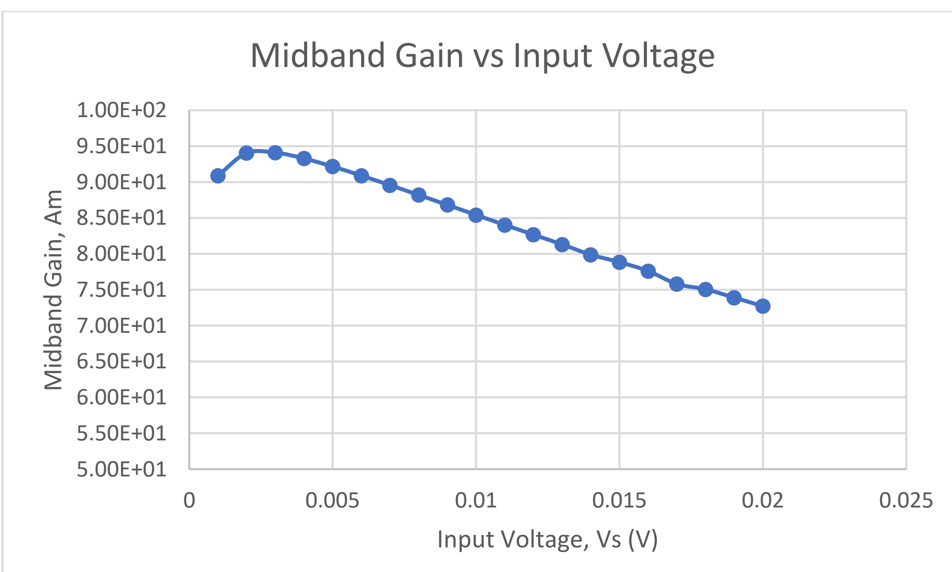
	f_{Lp3dB}	f_{Hp3dB}
Calculated	596.88	32.28M
Simulated	600	45M
% Difference	0.52%	28.267%

C Use f = 100kHz as midband frequency

I incremented the input voltage from 1mV to 30mV, I see that it stops being linear after around 15mV



The resulting midband graph is



The linear portion of the input voltage is within our specification of Av > 50 which is correct!

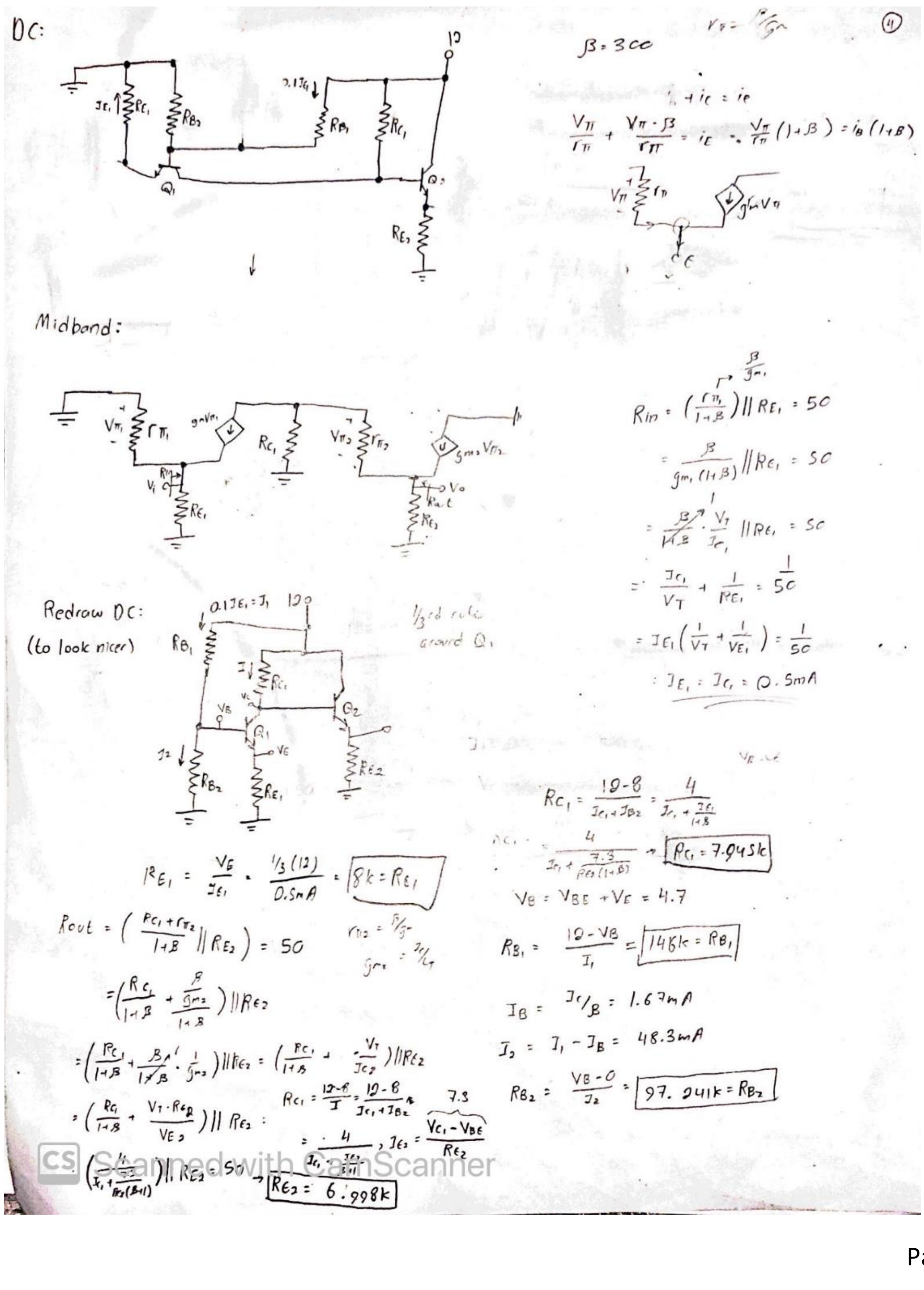
D

I took out the 50-ohm resistor, set my voltage amplitude to 10mV for 100kHz frequency, and measured input resistance to be: Rin = 10mV/2.95uA = 4k

Rout = 0.9V/515uA = 1.748k

Part 2

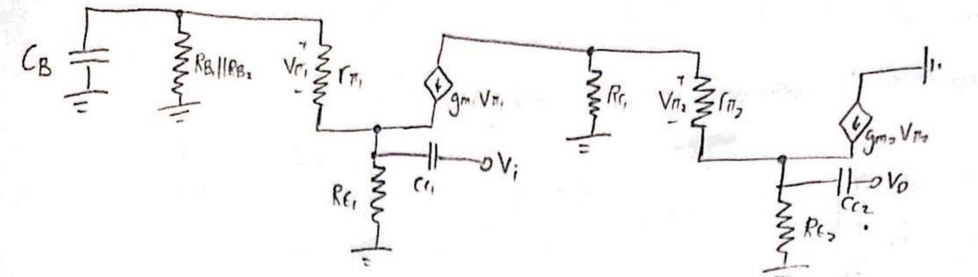
A Find resistor and capacitor values



Low freq:

$g_{m_1} = I_{C_1}/V_T = 2.0 \cdot 10^{-2} = g_{m_2}$ $\quad r_{\pi_1} = \beta/g_{m_1} = 15k = r_{\pi_2}$

Assume Q_1 and Q_2 are the same



$$\omega_{Lp_2} = \left[\left(\frac{R_{C_1} + r_{\pi_2}}{1+\beta} \| R_{E_2}\right) \cdot C_{C_2}\right]^{-1} = \left[75.408 \cdot C_{C_2}\right]^{-1}$$

SC around C_{C_1}: $\omega_{Lp_1} = \left[\frac{r_{\pi_1}}{1+\beta} \| R_{E_1} \cdot C_{C_1}\right]^{-1} = \left[49.525 \cdot C_{C_1}\right]^{-1}$

C_{C_1} and C_{C_2} set $\omega_{Lp\,3dB} = 1000 \cdot 2\pi$

$$C_{C_2} = \frac{1}{75.408 \cdot 1000 \cdot 2\pi} = \boxed{2.11\mu F}$$

$$C_{C_1} = \frac{1}{49.525 \cdot 1000 \cdot 2\pi} = \boxed{3.214\mu F}$$

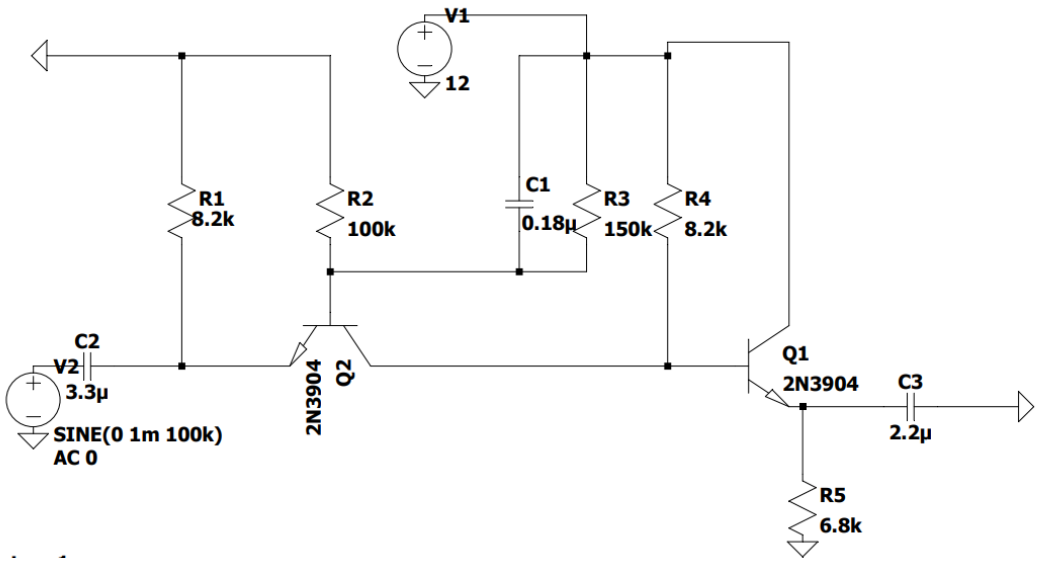
C_B should have a very small pole contribution.

$R_{C_B} = R_B \| R_{B_2} \| (r_{\pi_1} + (1+\beta) \cdot R_{E_1}) = 5.699 \cdot 10^4$

Let's say this cap is @ $\omega_{Lp_B} = 100$ (~1 decade left)

$$C_B = \frac{1}{100 \cdot 5.699 \cdot 10^4} = \boxed{0.17546\mu F = C_B}$$

B This is the circuit made using the resistance and capacitors values that were closest to the ones I calculated



I calculated Rin by attaching a voltage source to the input and measuring the peak voltage and peak current

Rin = Vin_{pp} / Iin_{pp} = 1mV / 20.029uA = **49.434 Ω** = $\mathbf{R_{in}}$

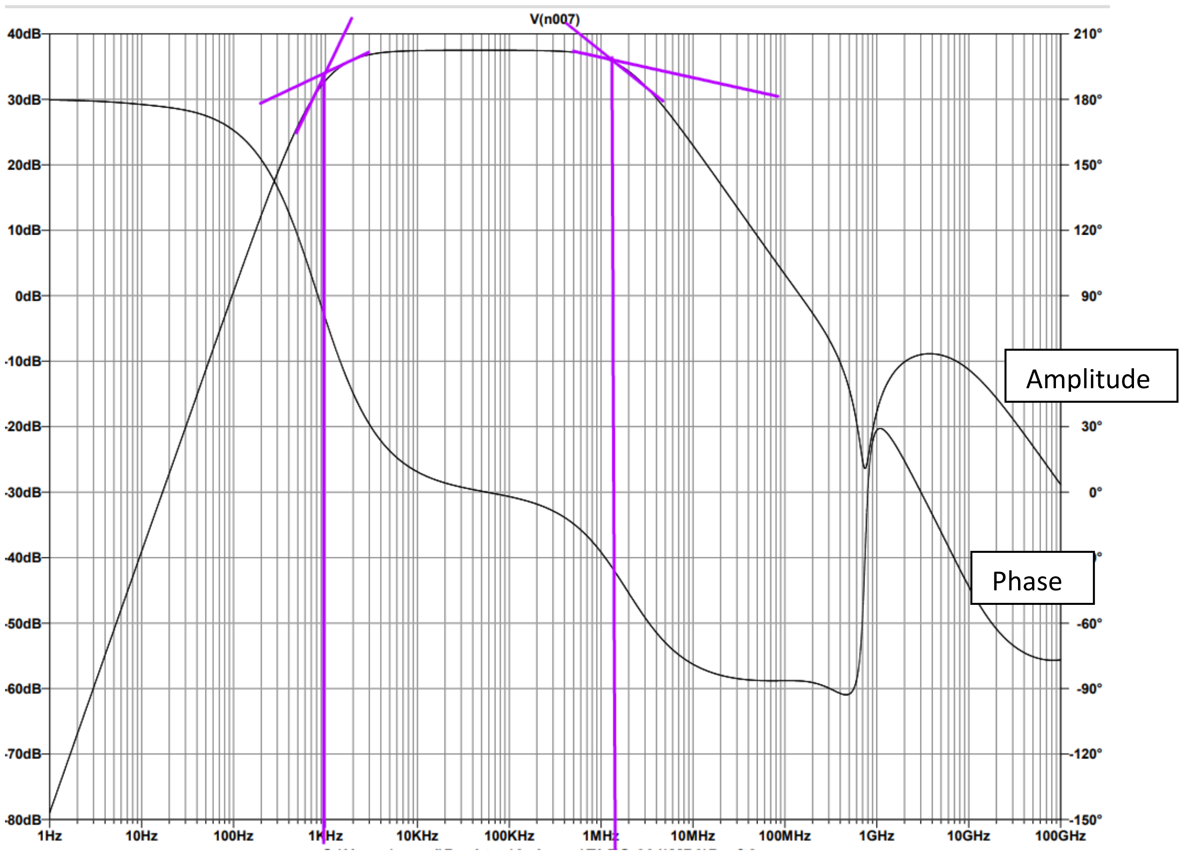
I calculated Ro by attaching a voltage source to the input and measuring the peak voltage and peak current

Ro = Vo_{pp} / Io_{pp} = 1mV / 20.15uA = **49.628 Ω** = $\mathbf{R_o}$

I attached a source voltage of 1mV and left the load open to measure midband gain at 100kHz

Am = Vo / Vs = 146.83mV / 1mV = **146.83 = Am**

C By loading the circuit I made, I resulted in the following bode plot



Based on the estimation of the bode plot I see that f_{Lp3dB} is located at around 1kHz which is what we wanted, and the f_{Hp3dB} is located at around 15MHz. Since the low-cutoff frequency matches what we wanted, our capacitor values must be correct!

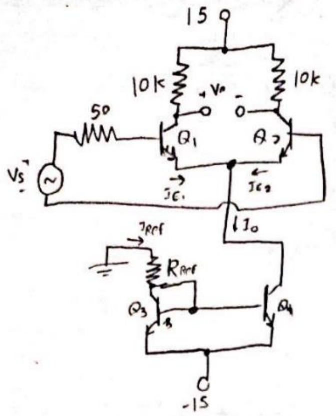
Part 3

A Wire up circuit

This is how I found the required resistance values

(6)

$\beta = 300$



$I_o = I_{C_1} + I_{C_2} = 1mA + 1mA = 2mA$

$I_{Ref} = \frac{V-(V_E+V_{BE})}{R_{Ref}} = I_{E_3} + I_{B_4}$

$I = I_{C_3} = I_{E_4} - I_{B_4}$

$V_{BE_3} = V_{BE_4}$

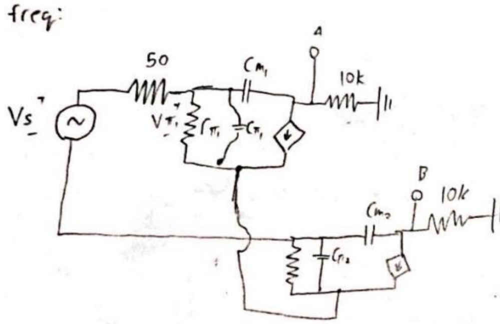
$I_{E_3} = I_{E_4}$

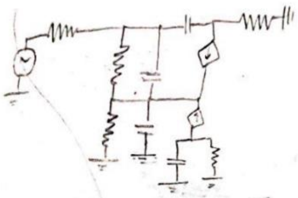
$I_{Ref} = I_o + 2I_{B_2} = I_{C_2} + 2I_{B_2} = I_{C_2}(1+2/\beta) = I_o(1+2/\beta)$

$I_{Ref} = 2mA(1+2/\beta) = 2.013mA$

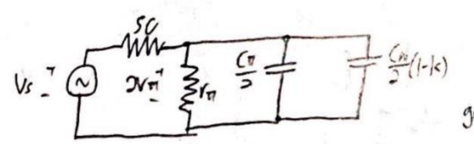
$R_{Ref} = \frac{V-(V_{EE}+V_{BE})}{I_{Ref}} = \frac{0-(-15+0.7)}{2.013mA} = 7.103k$

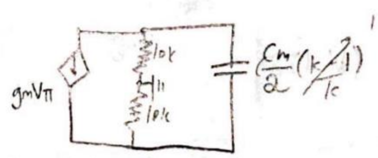
Low freq:





↓ Look nicer





$\frac{V_\pi}{V_s} = \frac{r_\pi}{2r_\pi + R_s} = 0.498$ $\frac{V_o}{V_\pi} = -g_m \cdot (R_{C_1} + R_{C_2}) = -800$

$\boxed{A_m = \frac{V_\pi}{V_s} \cdot \frac{V_o}{V_\pi} = 398.67}$

$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = 40m℧$, $r_\pi = \beta/g_m = 7.5k$, $C_\pi = 18p$, $C_\mu = 4p$

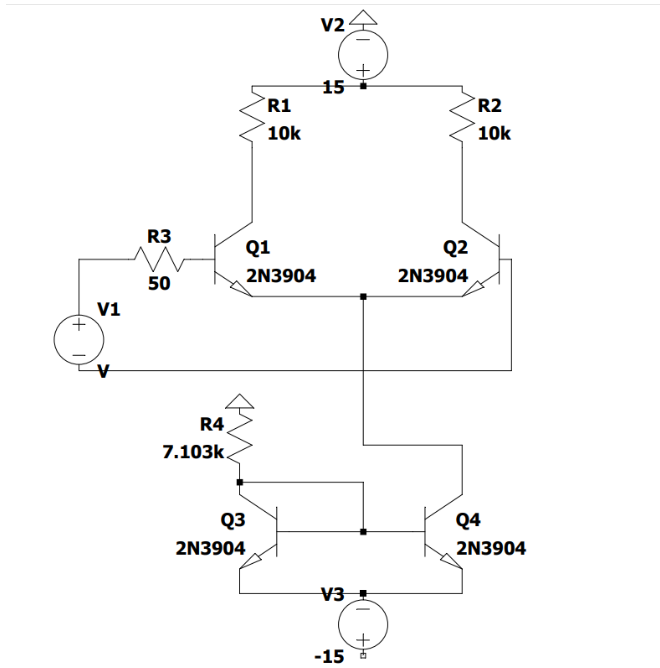
$k = \frac{V_o}{V_\pi} \cdot \frac{1}{2} = 400$

$\omega_{HP_1} = \left[\left(\frac{C_\pi}{2} + \frac{C_\mu}{2}(401)\right) \cdot (50 \| 2r_\pi)\right]^{-1} = 2.474 \cdot 10^7$ rad/s

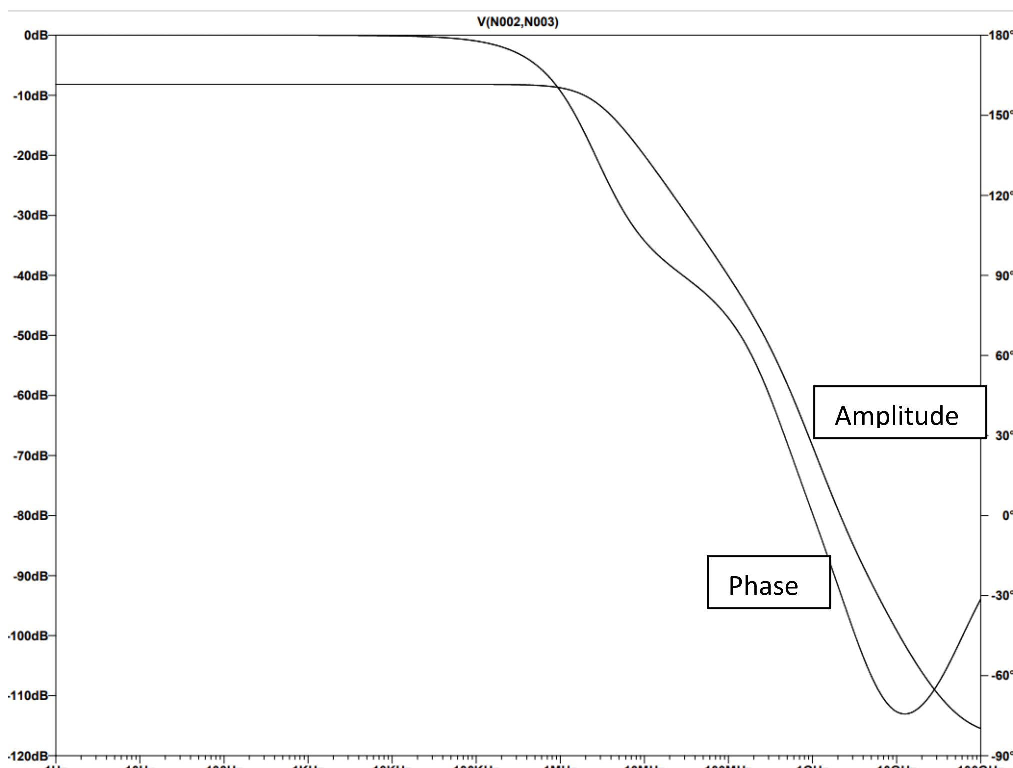
$\omega_{HP_2} = \left[\left(\frac{C_\mu}{2}(1-\frac{1}{k})\right) \cdot (10k + 10k)\right]^{-1} = 2.5 \cdot 10^7$ rad/s

$\omega_{HP3dB} = \sqrt{\frac{1}{\omega_{HP_1}^2} + \frac{1}{\omega_{HP_2}^2}} = 1.759 \cdot 10^7$ rad/s $\rightarrow$ $\boxed{f_{HP3dB} = 2.796 MHz}$

This is my resultant circuit



Here is the bode plot output



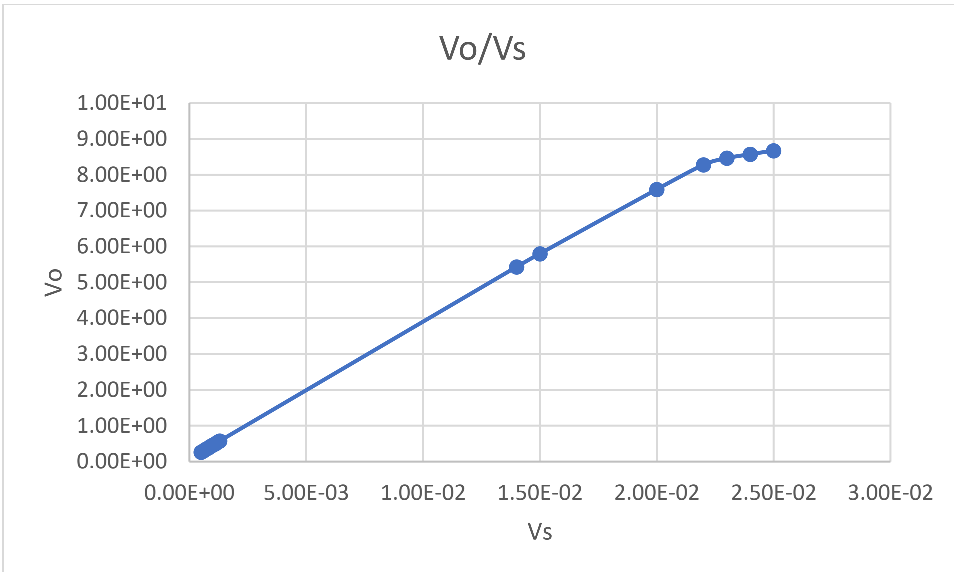
The f_{Hp3dB} is around 3.5MHz in this bode plot

B Find calculated poles

The calculated pole is f_{Hp3dB} = 2.796MHz. The % error is ~20%. This error may be due to the approximation technique used to find the pole on the graph. Nevertheless, the poles were somewhat close

C I chose 10kHz as my midband frequency

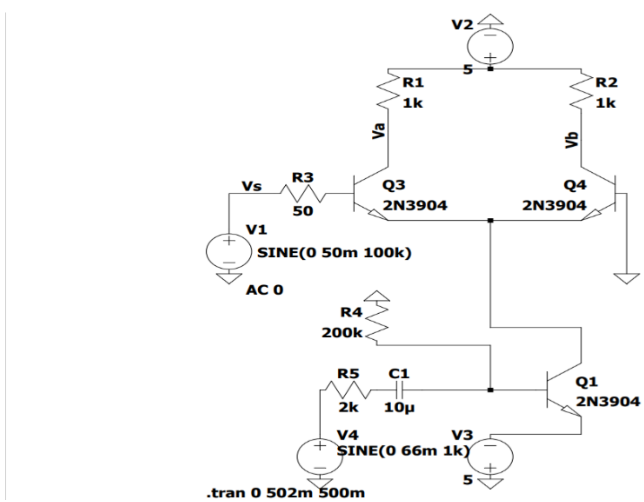
Increasing my voltage from 0.5mV to 25mV this is the graph I ended up with



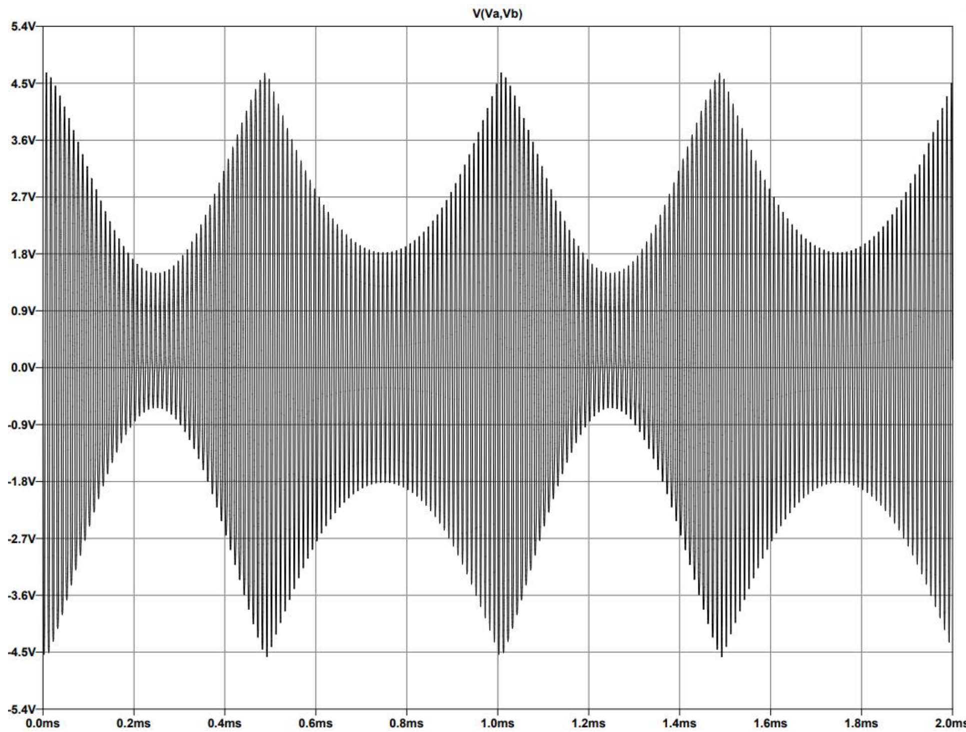
As you can see, the graph stops getting linear at around 22mV, as well the midband gain during the linear portions was around 500 – 350 which fit with the midband gain I calculated as 400.

Part 4

Here is my circuit "wired up"



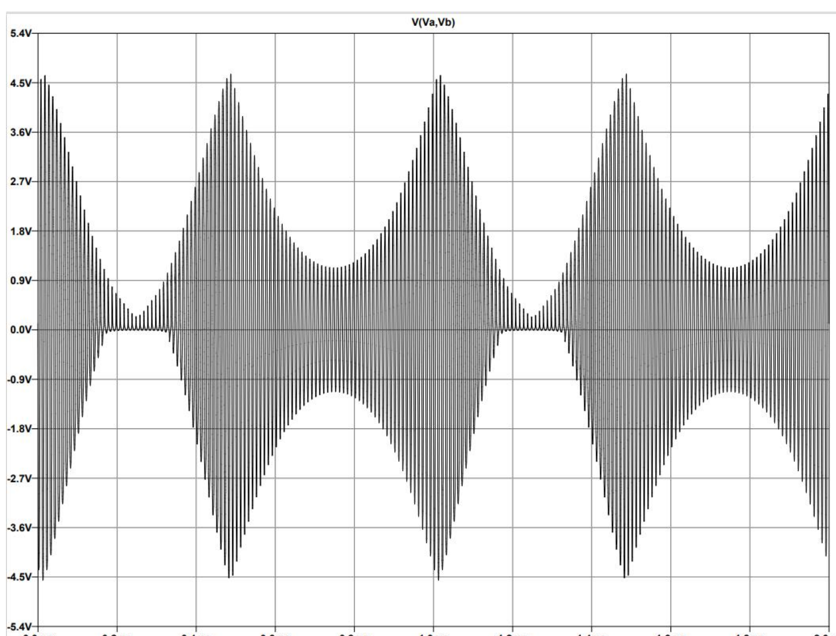
A Apply a 50m, 1kHz sine wave to input of modulator



The output appears to behave like "wave packets", it looks like waves made of waves

B Vary amplitude of input signal (between 10m and 100mVp) and show what happens.

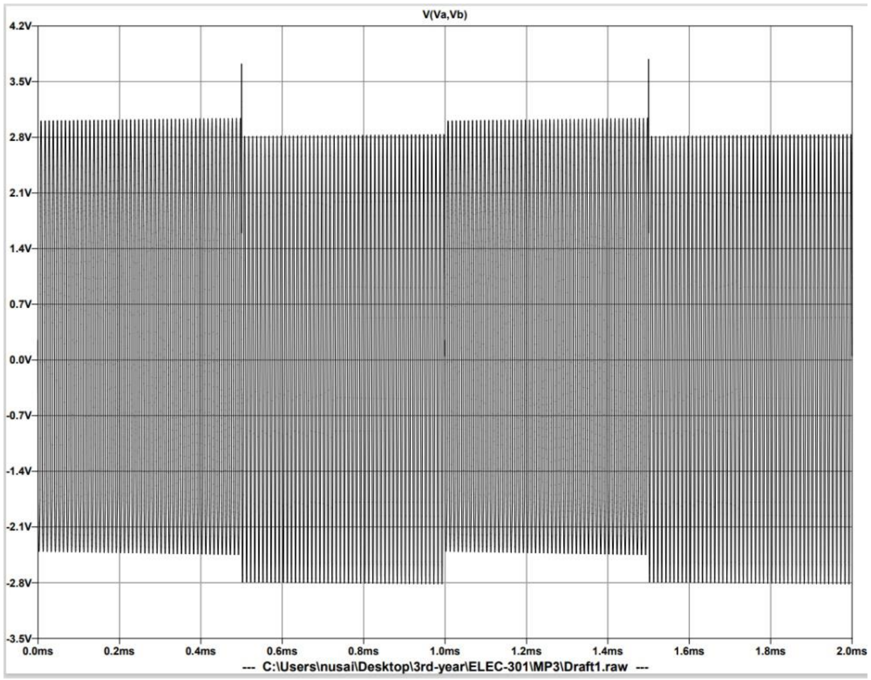
As the amplitude increases, the troughs of the wave packets get smaller as the peaks grow. At around 67 mV the wave packets appear to clip



Observe at the bottoms it starts flattening out

C Change input to a square wave

The square wave causes the output to also become squared.



At around 60mV of amplitude, the signal starts getting a bit of noise, and a slight slope is visible as well as a large outlier point on every other wave. At around this amplitude, the signal starts distorting.

The AM modulator works because the two waves from the input are multiplied together and the resultant waveform is the amplitude modulation. This exercise helped me learn how they work, as well as limits which is kind of cool considering this is how old AM hobby radios are made