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by Mohammed Ibrahim

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Module: SGEE4003 - Electronics I
Assignment Title: Analogue Circuit Design
Name: Mohammed Zeeshan Ibrahim
University number: 2224559
Date Submitted: 04/02/2023
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- ① EXCELLENT RESEARCH + APPROPRIATE CITATION LIST.
- ② INITIAL CALCULATIONS + TESTING IS WELL EXPLAINED.
- ③ REFINING GAIN AND BANDWIDTH IS EXPLAINED IN DETAIL.
- ④ OSCILLATOR SECTION IS GOOD.
- ⑤ BOTH CIRCUITS COMBINED USING 2 OP-AMPS.
- ⑥ GOOD ANALYSIS OF THE RESULTS AT EACH STAGE.
- ⑦ GOOD EVALUATION.
- ⑧ BRIEF CONCLUSION.

75-85

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Executive Summary

The main goal of this assignment was to design a Class A amplifier to achieve the given specification. An oscillator was also designed and added to the circuit to provide the amplifier with a suitable input signal. Research was completed beforehand on amplifier configurations, op-amp configurations, negative and positive feedback, oscillator types and tuned amplifiers. Researching amplifier configurations gave an insight on various different amplifiers and their applications along with op-amps. Two op-amps were used in the oscillator. One of them being a buffer amplifier and the other being an inverting amplifier. Negative feedback was researched and later added into the circuit via a potential divider. This then made the gain closer to the required value. Oscillators were researched and implemented in the circuit to give out the specified input signal and centre frequency. Tuned amplifiers were lastly researched but could have been implemented in the circuit in order to obtain the specified bandwidth without compromising the gain and centre frequency. Before simulating the circuit, calculations were completed and once the circuit was built, these values were fine tuned. These calculations consisted of currents, resistances, capacitor values, gain etc. Once the circuit was built, it was tested, analysed and improved. After each analysis, it was improved by fine tuning component values, adding negative feedback and adding an oscillator. Once completed, the specified values were achieved except for the bandwidth. A tuned circuit would need to be implemented to achieve the correct bandwidth without compromising the gain.

Planning

Research will first be carried out to gain knowledge on relevant amplifier related topics. Knowledge on these topics will be implemented in the design process. The amplifier components will be designed, calculated and simulated following certain conditions. Tests will be carried out to ensure the circuit satisfies the criteria and will be analysed and evaluated.

Reflection

Knowledge on various amplifier topics were achieved along with the factors that affect the overall performance of the amplifier. Such negative feedback effecting the gain. This assignment overall introduced circuit design and this knowledge will be built upon as the learning progresses in future. It also gave an understanding on why it is important to complete testing and do analysis in order to improve the equipment. This is a necessity in engineering practices. It also showed how calculations have an impact on the design process and how adjustments can be made to improve the quality of the system. This also will impact further lifelong learning on other relevant electronics topics.

Research Into Amplifier, Oscillators and Feedback

Amplifier Configurations and Choice of Transistor:

Class A - Class A amplifiers use the same switching transistor for both halves of the output waveform and the output transistor has a constant flow of DC biasing current (I_{CQ}) despite there being no input signal. Hence the output transistor doesn't turn off, which wastes energy, as the waveform shows below (Aspencore, 2022a):

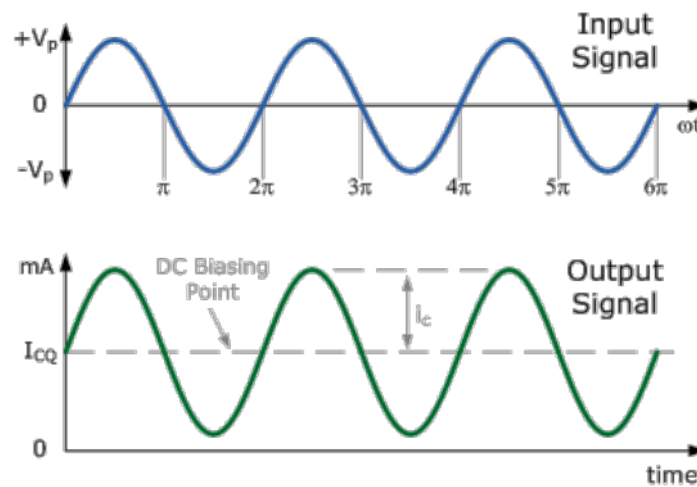


Figure 1 Class A Output Waveform - (Aspencore, 2022a)

Class B - In a Class B amplifier, there is no bias due to Class B operation only being provided when the DC bias exits the transistor when the AC voltage is applied. It uses two transistors in which each of them conduct in opposite half cycles. Both provide a full cycle of the output signal (Boylestad & Nashelsky, 2013, p. 717).

Thus, a Class B amplifier has a higher efficiency compared to a single transistor Class A amplifier (Boylestad & Nashelsky, 2013, p. 718).

This type of amplifier, however, suffers from crossover distortion (Aspencore, 2022a).

The output waveform for this is shown below:

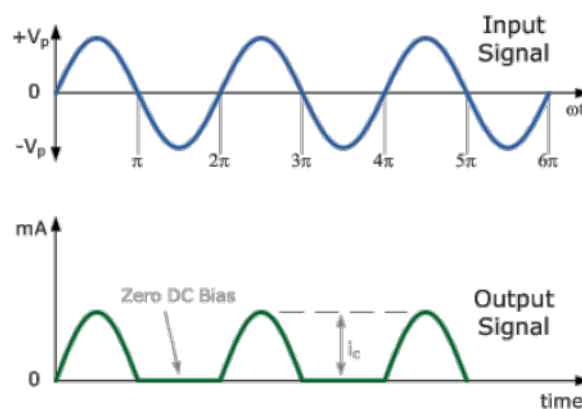


Figure 2 Class B Output Waveform - (Aspencore, 2022a)

The choice of transistor for this assignment is a 2N3904. These are featured in class A common emitter amplifiers, which are known for producing a large output voltage from a small input signal. This is a requirement since the specification demands a high gain of 50 (AspenCore, 2022b).

A class B amplifier could have been used; however, they suffer from crossover distortion due to them needing to switch on and off, unlike a class A amplifier. Class A amplifiers are also simple to design and construct when compared to a class B or class AB amplifier (Aspencore, 2022a).

Operational Amplifier Configurations:

Inverting Amplifier - The inverting amplifier is the most used constant – gain amplifier, in which a fixed or constant gain is multiplied by the input to obtain an output. This is set with the input resistor (R_1) and feedback resistor (R_f) below (Boylestad & Nashelsky, 2013, p. 641):

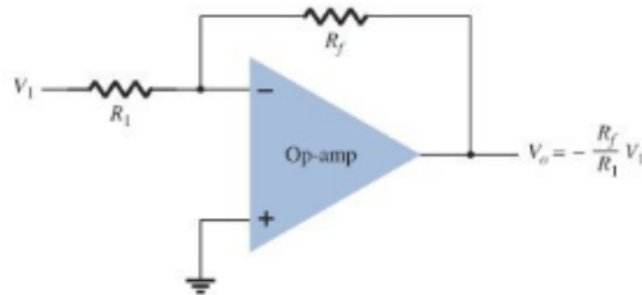


Figure 3 Inverting Amplifier Configuration (Boylestad & Nashelsky, 2013, p. 641)

Non - Inverting Amplifier – According to Teja, “a non-inverting amplifier uses a voltage-divider-bias negative feedback connection”. He also states that resistors (R_1 and R_f) with certain values can be used to obtain a desired voltage gain (see figure 4). For a DC input, the input polarity is identical to the output polarity. For an AC input, the input signal is in phase with the output signal, which suggests the voltage gain is positive (2022).

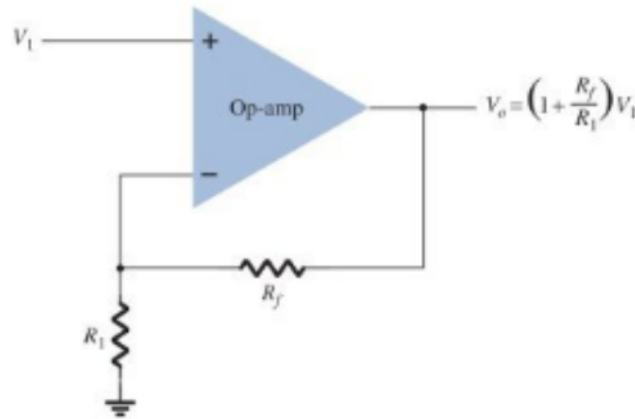


Figure 4 Non - Inverting Amplifier Configuration (Boylestad & Nashelsky, 2013, p. 642)

Negative and Positive Feedback:

Negative feedback – this takes a portion of the output and subtracts it the input so that the output balances with the input (see figure 5). Hence if there is a change in the input, there is a similar change in the output. An example of this is a voltage follower, where the output is connected to the negative terminal of the amplifier. So, if the input was given 1V, the output will also read 1V due to 100% negative feedback and the difference between inverting and non-inverting pins being 0V, (Vivekanand, 2021).

Bird states that “100% negative feedback is obtained by connecting the output directly to the inverting terminal” which then supports what Vivekanand previously said. Hence, negative feedback reduces the gain (2010, p. 250).

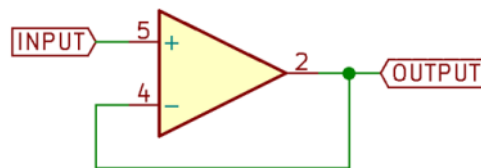


Figure 5 Negative Feedback in An Op-Amp (Vivekanand, 2021)

Positive feedback - Vivekanand states that a “non-inverting amplifier circuit can be modified a little bit to create a circuit that has positive feedback”. This is done by adding a potential divider and switching the inverting and non-inverting inputs to make the inverting input become the signal input and the non-inverting input to be the terminal that receives the feedback from the potential divider output, as shown below. This will then increase the gain, whereas figure 4 shows the potential divider connected to the negative terminal, which reduces the gain (2021).

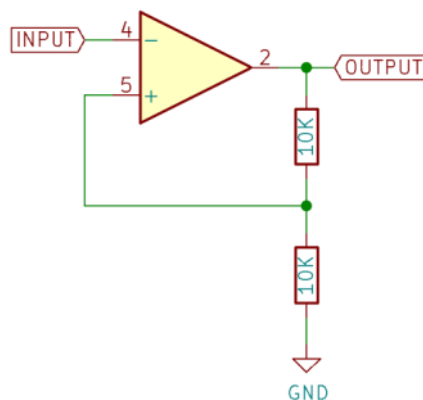


Figure 6 Positive Feedback in An Op-Amp (Vivekanand, 2021)

Oscillators and Their Types:

Crystal Oscillator - The operation frequency of these oscillators at a thinner size can offer a high frequency of operation. Such as, a 0.15mm thick quartz crystal can operate at 15MHz. The stability and frequency depends on the crystal dimensions, geometric orientation of the crystal's cuts and the crystal type. This makes them very accurate, due to being able to make these changes to obtain a desired frequency. The crystal is known to sit between two electrodes that naturally creates an oscillating signal (Wendt, 2020).

Wien Bridge Oscillators - AspenCore states that the *"circuit is based on a frequency-selective form of the Wheatstone bridge"*. It uses a feedback circuit which contains a series RC circuit and parallel RC circuit using identical component values, that causes a phase delay or *'phase advance circuit depending on the frequency'*. They also state that it can create a high range of frequencies. The circuit can also be unstable if the gain of the amplifier is too small or large (see figure 7) (2022c).

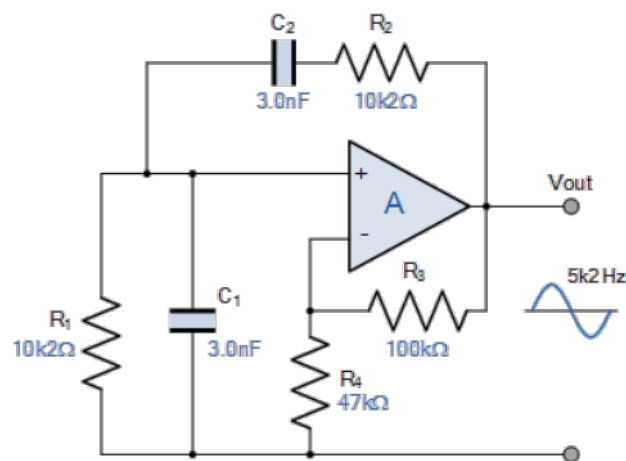


Figure 7 Wien Bridge Oscillator Circuit (AspenCore, 2022c)

Tuned Amplifiers:

Single Tuned Amplifier operation - the applied signal frequency is made equal to the parallel circuit frequency by altering the capacitor value 'C' within the parallel tuned circuit (see figure 8). The signal frequency now has high impedance, and all the other frequencies have a low impedance. The tuned amplifier then selects the high impedance frequency and amplifies it (tutorialspoint, 2022).

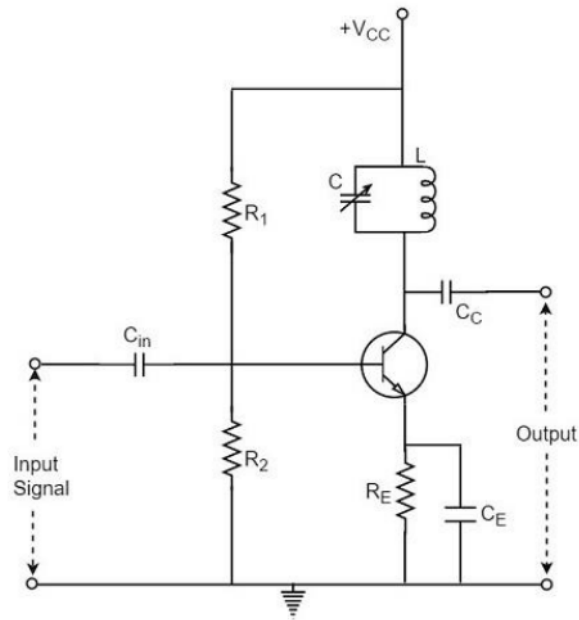


Figure 8 Single Tuned Amplifier Circuit - (tutorialspoint, 2022)

Design, Method, Calculations and Testing

a) DC Conditions:

The initial element of the design process was to select and obtain a power supply for the transistor. This was conducted by choosing a DC power supply voltage. Values of 6 - 12V are common. 12V (VCC) was chosen for this.

The transistor chosen was an NPN 2N3904 and a data sheet was obtained for this to acquire further values (Semiconductor Components Industries, LLC, 2021). This transistor was chosen due to having the ability to be simulated on MultiSim and it needed to have a small signal and low frequency.

The datasheet required interpretation to determine the quiescent current suitable for the design. This is the collector current when zero amount of signal is transmitted. 5mA was chosen for the quiescent current (IQ) which should've been around 10 to 20% of the transistor's I_{cmax} figure (see appendix E).

The value for the load resistor (RL) required calculation. The purpose of this is to provide the collector with approximately half of the supply voltage and was done using this equation:

$$\begin{aligned} R_L &= \frac{V_{CC} - V_C}{I_Q} \\ R_L &= \frac{12 - 6}{0.005} \\ R_L &= 1.2K\Omega \end{aligned}$$

Equation 1 Load Resistor

The value for RE then needed calculation. The was to provide efficient bias stabilisation. The emitter voltage (VE) also needed to be estimated to do the calculation. This needed to be around 10% of VCC, which was 1.2V. RE was then calculated using the equation below:

$$\begin{aligned} RE &= \frac{VE}{IQ} \\ RE &= \frac{1.2}{0.005} \\ RE &= 240\Omega \end{aligned}$$

Equation 2 Emitter Resistor

The base current IB then needed to be estimated by dividing the collector current by the Hfe value of the transistor. The data sheet was acquired to obtain the HFE value in order to complete the calculation (Semiconductor Components Industries, LLC, 2021) (see appendix E). The calculation was then completed below:

$$\begin{aligned} IB &= \frac{IC}{Hfe} \\ IB &= \frac{5 \times 10^{-3}}{150 \times 10^{-3}} \\ IB &= 33.33mA \end{aligned}$$

Equation 3 Base Current

The base voltage (VB) was then calculated. This simply needed to be 0.7V higher than VE to make sure the input signal is biased on the linear part of the transistor input characteristic. The calculation is as shown below:

$$\begin{aligned} VB &= VE + 0.7 \\ VB &= 1.2 + 0.7 \\ VB &= 1.9V \end{aligned}$$

Equation 4 Base Voltage

The DC bias network current required calculation. Adequate bias stability needed to be implemented in the circuit, so the current flowing through R1 and R2 were to be about 10 times larger than the base current (IB), hence the equation:

$$\begin{aligned}IR1 &= IB \times 10 \\IR1 &= 33.33 \times 10 \\IR1 &= 333.33mA\end{aligned}$$

Equation 5 DC Bias Network Current

The resistance for R1 then required calculation. The equation below determined this:

$$\begin{aligned}R1 &= \frac{VCC - VB}{IR1} \\R1 &= \frac{12 - 1.9}{333.33 \times 10^{-3}} \\R1 &= 30300\Omega\end{aligned}$$

Equation 6 Resistor 1

Finally, the resistance for R2 was simply calculated by dividing the base voltage by the bias network current:

$$\begin{aligned}R2 &= \frac{VB}{IR1} \\R2 &= \frac{1.9}{333.33 \times 10^{-3}} \\R2 &= 5700\Omega\end{aligned}$$

Equation 7 Resistor 2

The initial circuit was then built and tested (see analysis 'a').

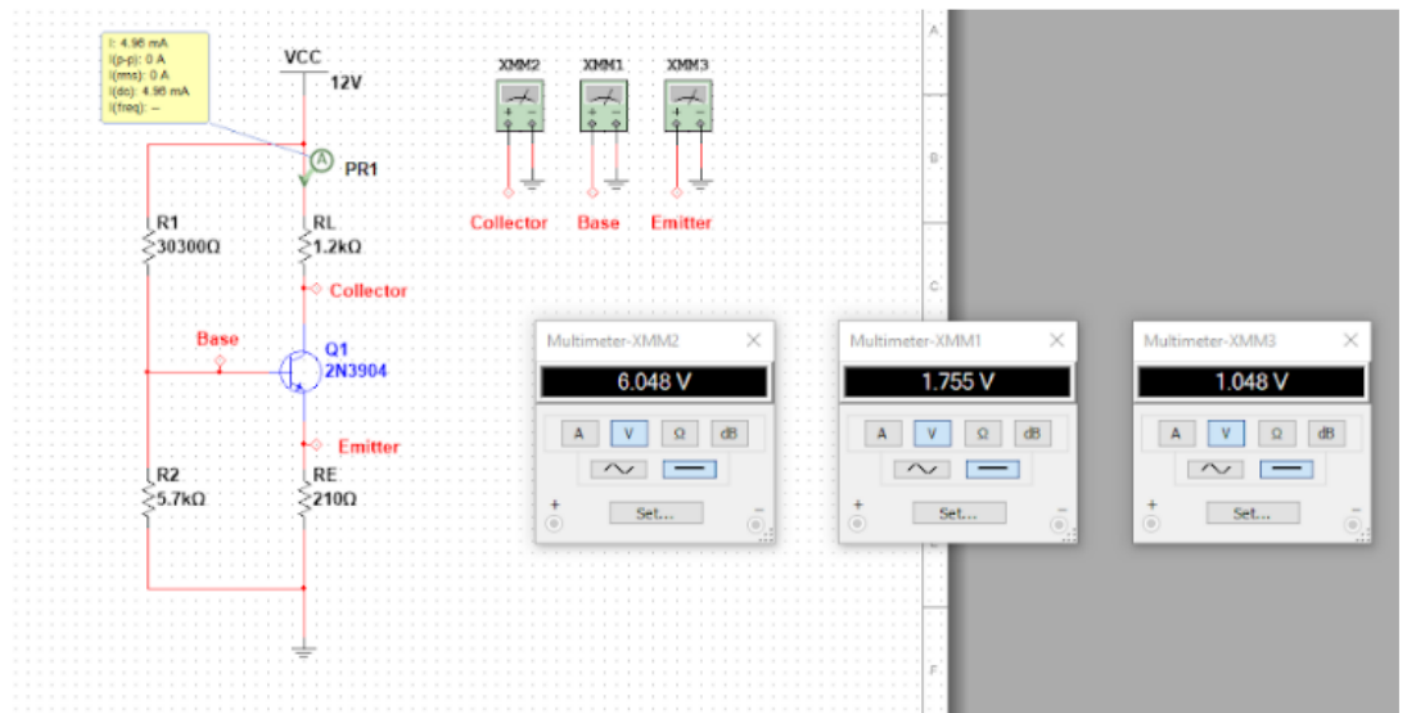


Figure 9 Collector, Base and Emitter Voltage Measurements

b) AC Components:

The initial values for C1, C2 and C3 needed calculation. C1 and C2 are coupling capacitors that block DC voltage at the input and output to ensure bias stabilisation isn't affected. C3 prevents AC voltage appearing at RE. AC voltage at the emitter will be in phase with the base signal, which will overall reduce the amplifier gain. X_C was assumed to be 1Ω for low capacitive reactance at 1MHz:

$$\begin{aligned}C &= \frac{1}{2\pi f X_C} \\C &= \frac{1}{2\pi \times 1 \times 10^6 \times 1} \\C &= 160nF\end{aligned}$$

Equation 8 Capacitors

The gain was now calculated using $V_{in} = 100mV$ and $V_{out} = 10.6V$ which was obtained from the voltage probes within the circuit (see figure 10). The equation for gain is as shown below:

$$\begin{aligned}GAIN &= \frac{V_{OUT}}{V_{IN}} \\GAIN &= \frac{10.6}{100 \times 10^{-3}} \\GAIN &= 106\end{aligned}$$

Equation 9 Amplifier Gain

The 100mV (P-p) input voltage was added along with the 3 capacitors. The gain currently measured to be 106.

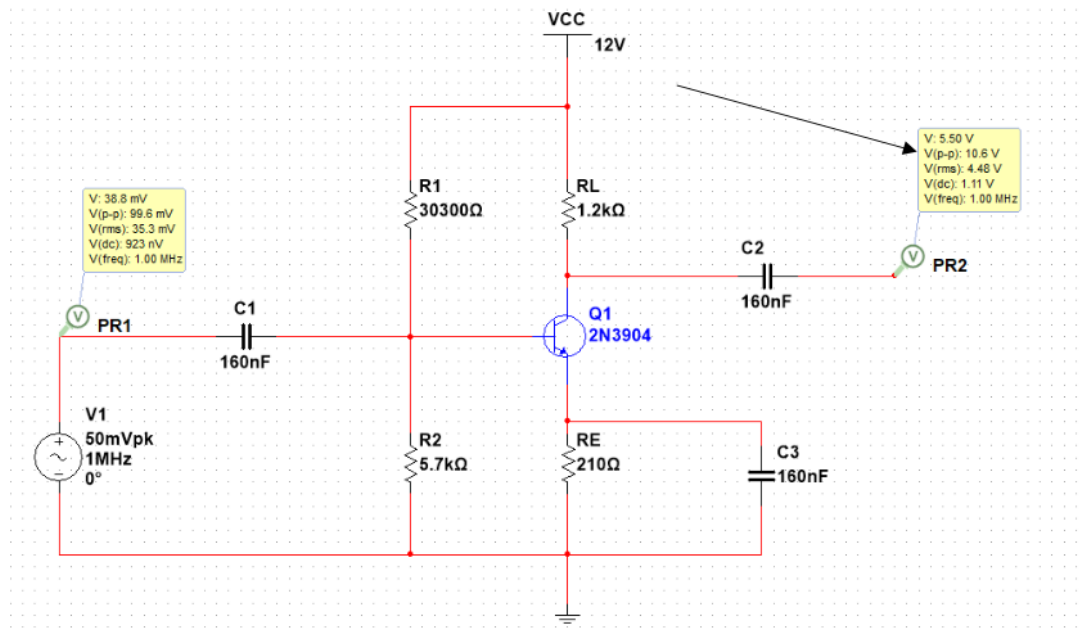


Figure 10 Circuit with Added AC Components

The bandwidth and centre frequency were now tested (see analysis 'b' and appendix A).

c) Refining the Design for Bandwidth:

The circuit required testing, so a variable resistor was implemented in the circuit, in a way that it can alter the input voltage which also increased or decreased the output voltage. The variable resistor was adjusted to obtain half of the output voltage of 10.6V once the variable resistor reached 1030Ω. This was the value of the input impedance Z_{in} :

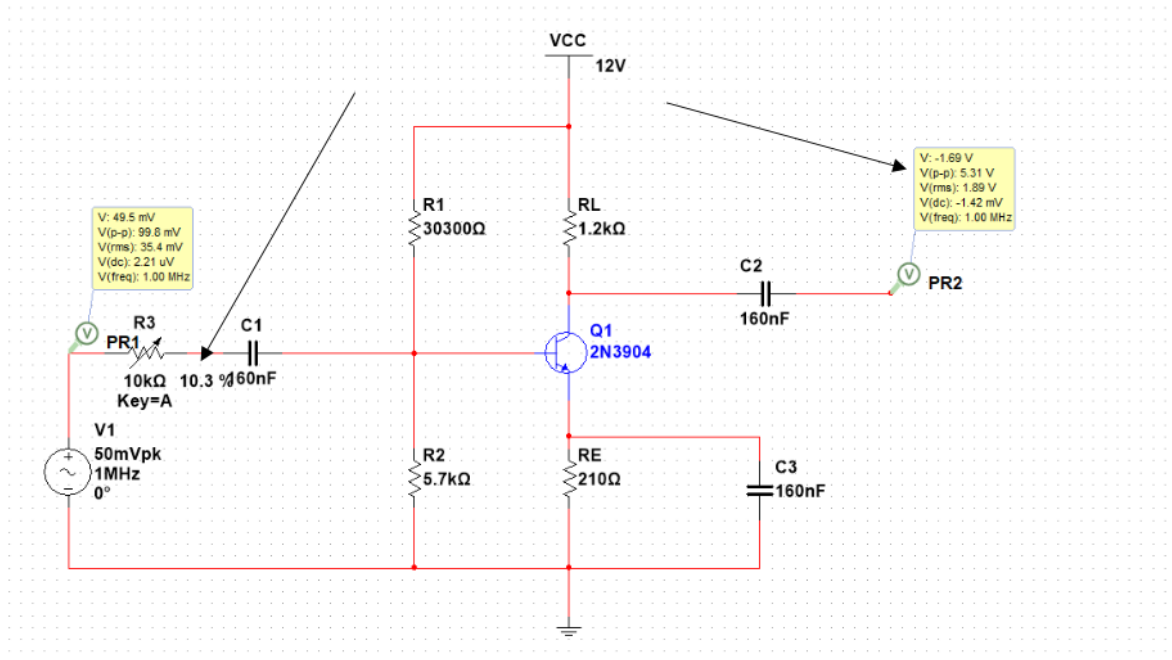


Figure 11 Half Output Voltage at 10.3% R3

To narrow the lower frequency band, the value of C1 required re-calculation. The lower band is 850KHz. Z_{in} was the value used for $x C$:

$$C = \frac{1}{2\pi f Z_{in}}$$

$$C = \frac{1}{2\pi \times 850 \times 10^3 \times 1030}$$

$$C = 182pF$$

Equation 10 New C1 Calculation

To narrow the upper frequency band and reduce higher end amplification, C4 required calculation. The upper band is 1150KHz. The value for xC used was RL, which was also the value of Zout. After adjustment of the calculated value, the final value for C4 was 100pF:

$$\begin{aligned}C &= \frac{1}{2\pi f Z_{out}} \\C &= \frac{1}{2\pi \times 1150 \times 10^3 \times 1200} \\C &= 115pF\end{aligned}$$

Equation 11 C4 Calculation

The purpose of narrowing the bands was to attempt to obtain the bandwidth of 350KHz. C4 was then applied to the circuit and the bandwidth was analysed (see analysis 'c' and appendix B).

d) Improving the Design for Gain:

Negative feedback was introduced to reduce the gain by splitting RE into two resistors and C4 was added. RE1 and RE2 were adjusted until the optimum value for gain could be acquired, whilst still keeping the sum of them at 210Ω:

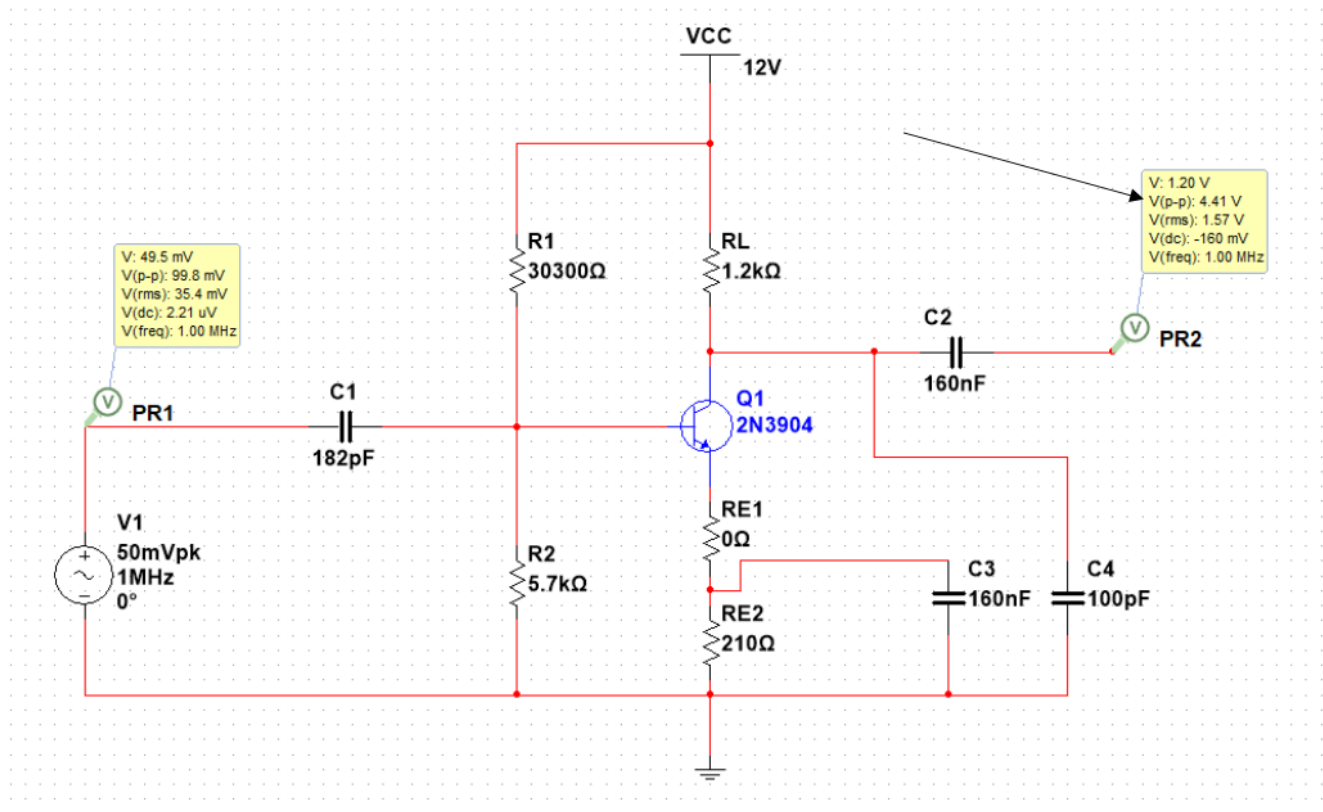


Figure 12 Negative Feedback Added to Circuit

The circuit was tested for bandwidth and centre frequency (see analysis 'd' and appendix C).

e) Adding an Oscillator:

The oscillator inductor required calculation. The equation below was used to calculate L1, using 1MHz for fo and the initial values for C1 and C2 in figure 13, which were 100pF:

$$L1 = \frac{1}{4\pi^2 C f_o^2}$$
$$L1 = \frac{1}{(4\pi^2 \times 100 \times 10^{-12} \times (1 \times 10^6)^2)}$$
$$L1 = 0.25mH$$

Equation 12 Inductor L1

The capacitors C1 and C2 in the figure 13 were adjusted to 142pF to acquire a frequency of 1MHz. Inverting amplifier U2 was then adjusted to output a voltage of 100mV(P-p), which was also going to be Vin for the designed amplifier circuit. The gain for U2 was calculated using the equation below. Vout was the 6V output from U1.

$$GAIN = \frac{VOUT}{VIN}$$
$$GAIN = \frac{100 \times 10^{-3}}{6}$$
$$GAIN = 0.0167$$

Equation 13 U2 Gain

A 100mV(P-p) output was then obtained by adjusting R3 and R4 in figure 13. R3 was taken to be 10KΩ. R4 was then calculated using the equation shown.

$$R4 = R3 \times GAIN$$
$$R4 = 10000 \times 0.0167$$
$$R4 = 166.67\Omega$$

Equation 14 Resistor 4

(See analysis 'e')

f) Building the Final System:

The values calculated were added to the oscillator. It was now combined with the amplifier. Its output from op-amp U2 was connected to the amplifier's input, replacing the signal generator. The circuit was now fully tested (see analysis 'f' and appendix D).

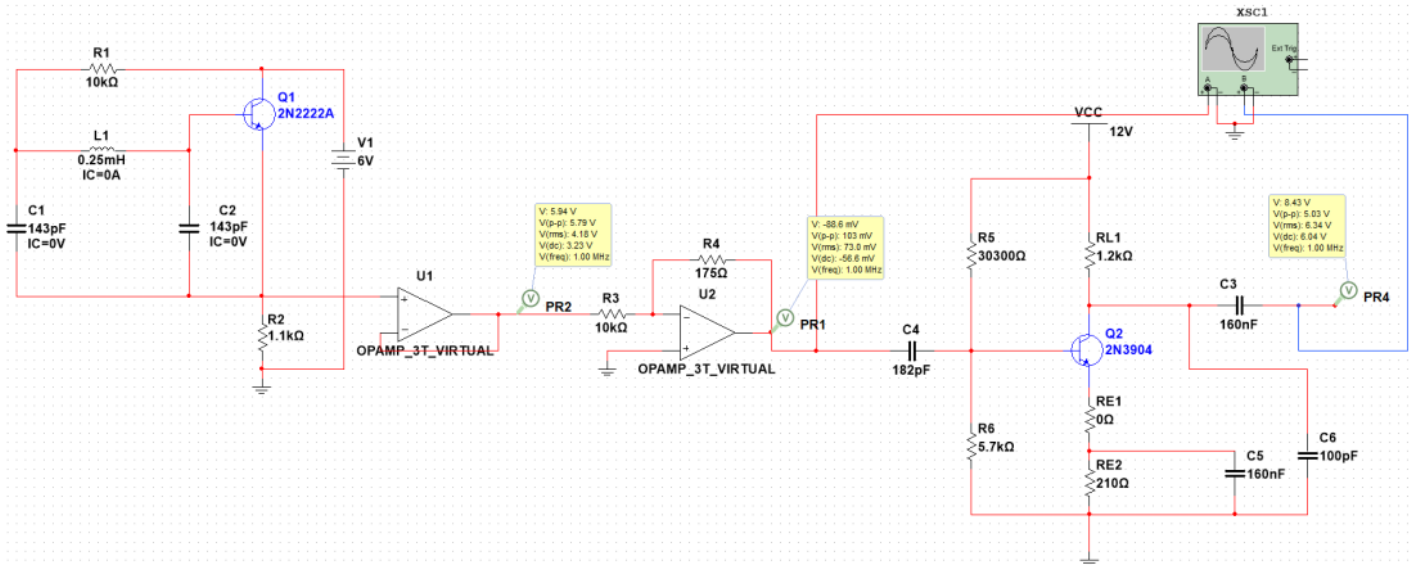


Figure 13 Combined Circuits

Analysis of Results at Each Stage

- a) The initial circuit was built and tested using multimeters to measure the collector, base, and emitter voltages to ensure they were roughly correct. A current probe was also placed to ensure the correct quiescent current (5mA) was present. The value of R_E was altered slightly to make the collector voltage half of the supply voltage. The collector voltage was roughly half of VCC, the emitter voltage was 0.5V from 10% of VCC after altering R_E and the base voltage was about 0.15V off from the calculated base voltage 1.9V (see figure 9).
- b) From the results, the initial result for bandwidth obtained was around 24MHz with the centre frequency reading around 2MHz. The upper and lower bands required narrowing. The gain was also too high at 106 and needed reducing (see appendix A).
- c) After refining the design for bandwidth, it dropped significantly and ended up being around 4MHz. This was due to narrowing the upper and lower band by adjusting C1 and C4 in figure 12. The specified centre frequency was then obtained. The specified bandwidth and gain were still not obtained, and more adjustments needed to be made (see appendix B).
- d) After introducing negative feedback, the gain was reduced 44.1 which was close to the specification, but still not there (see figure 12). Adjustments were made to find middle ground between gain and bandwidth without also compromising the centre frequency. This was due to bandwidth and gain affecting each other when adjusting either of them. The specified bandwidth was still not achieved, still reading a value of 4MHz (see appendix C).
- e) The specified input voltage of 100mV(P-p) was now achieved by adjusting R4 on op-amp U2, which was connected the amplifier (see figure 13).
- f) The output waveform of the oscillator was compared with the amplifier. A gain of approximately 50 was obtained with a centre frequency of 1MHz which were both the specified values (see figure 13). The oscillator waveform was roughly sinusoidal whilst the amplifier's waveform looked closer to a sine wave and roughly 100mV(P-p) was achieved (see appendix D).

Evaluation

From the results and analysis, the amplifier almost satisfies the criteria. An input signal of 100mV(P-p) was achieved with a gain of 50 along with a centre frequency of 1MHz (see figure 13). The only specification that could not be obtained was the bandwidth. The closest bandwidth to 350KHz that could be obtained was 4.4MHz which was very far off the specified value (see appendix C). This was due to the centre frequency being shifted when adjusting capacitors C1 and C4 in figure 12, to narrow the upper and lower band whilst also affecting the gain. The correct bandwidth could be achieved doing this however, the gain would have been reduced and the centre frequency would be shifted, hence the wrong band of frequencies being amplified. Middle ground was eventually found by going through several iterations of altering the bandwidth and gain, but the bandwidth was compromised. It was still able to amplify the correct frequencies due to the centre frequency being 1MHz, however there are a range of unwanted frequencies in the final bandwidth achieved. Thus, it was better to compromise the bandwidth rather than the centre frequency and gain. A solution to achieving the specified bandwidth and would be to replace the load resistor with a tuned circuit containing a resistor and variable capacitor in parallel with each other. The variable capacitor can be adjusted, making the applied frequency equal to the parallel circuit frequency. Since the signal frequency has a high impedance and all the other frequencies have low impedance, the tuned circuit will select the high impedance frequency and amplify it. Hence amplifying a lower band of frequencies whilst not compromising the gain and retaining the 1MHz centre frequency. Having U1 as the buffer amplifier ensured the impedances within each circuit did not react with each other, otherwise all calculated values would be affected.

Conclusion

Overall, most of the specification was achieved, except the bandwidth and an understanding was made on the use of different types of amplifiers and their applications through research. Such as using a class B amplifier for better efficiency than a class A but risking the effect of crossover distortion and using a tuned circuit to obtain the specified bandwidth. Calculations were also vital to the design process, as it obtains close to specified output values. Components just required some fine tuning. Testing the circuit after each stage showed how it improved when certain adjustments were made, such as adding negative feedback.

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Appendices - Results

Appendix A: - AC Components

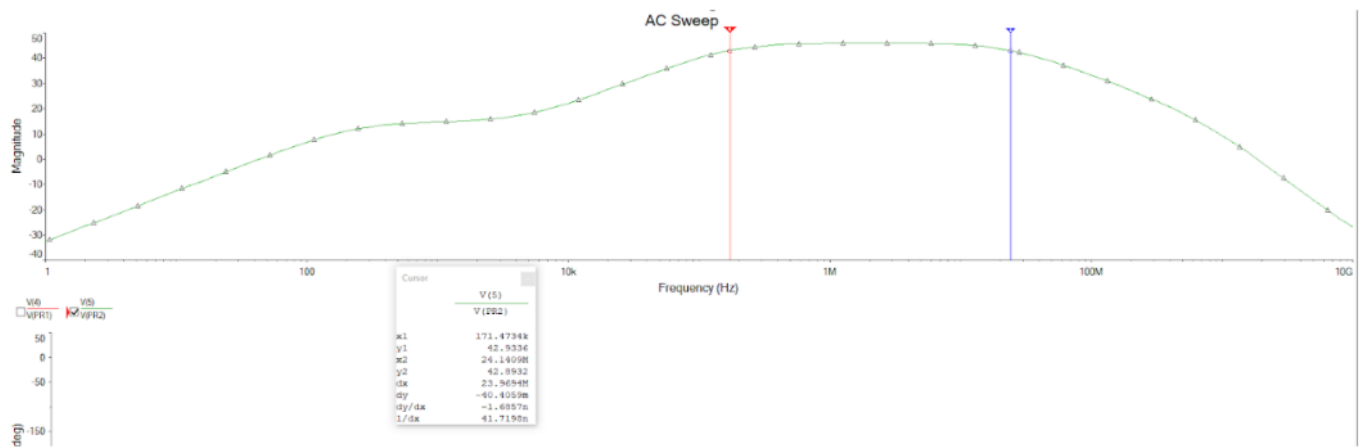


Figure 14 Initial Bandwidth Measurement After Adding AC Components

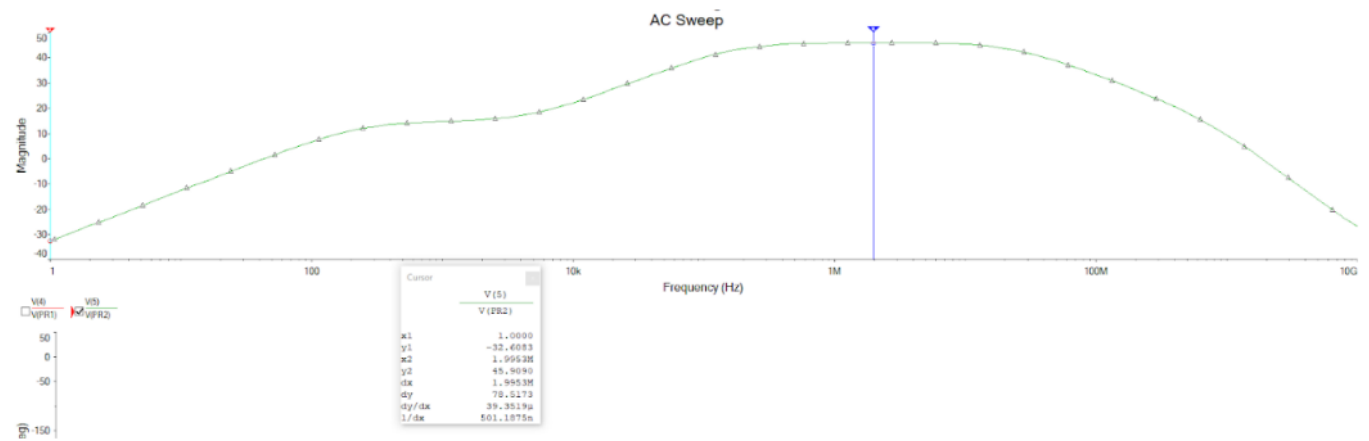


Figure 15 Initial Centre Frequency Measurement After Adding AC Components

Appendix B: - Refining the Design for Bandwidth

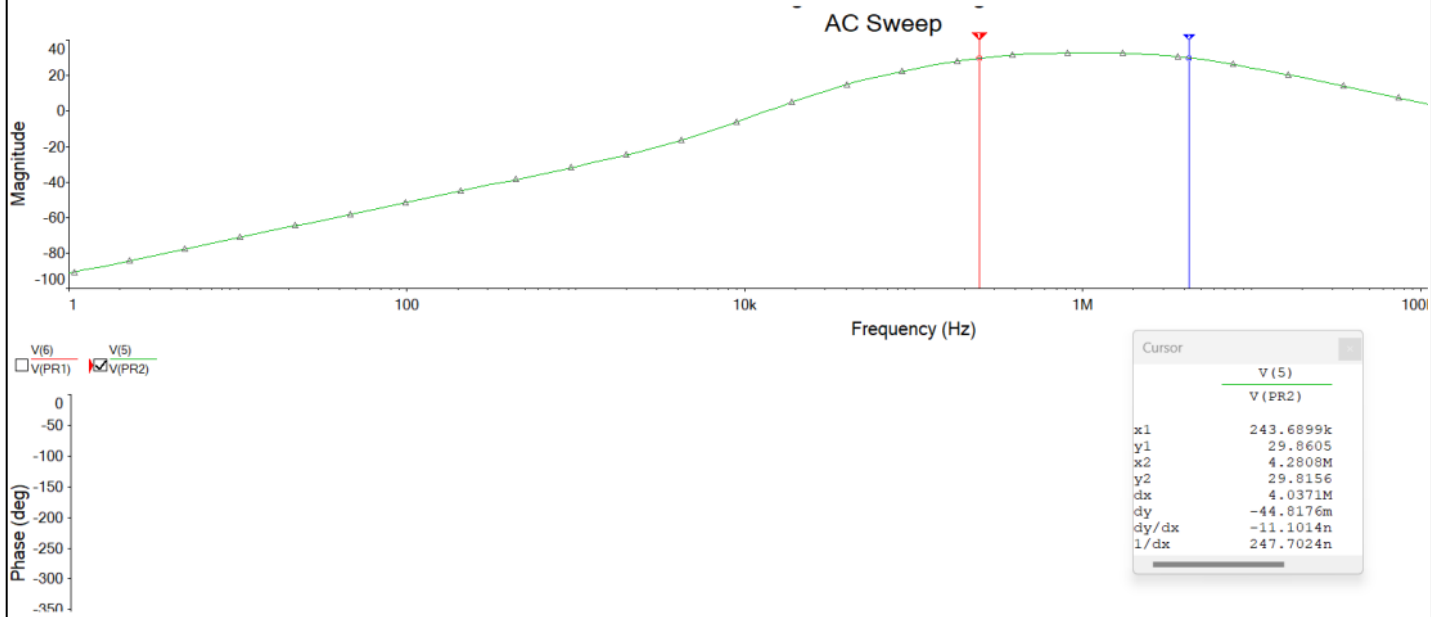


Figure 16 Bandwidth After Refining the Design

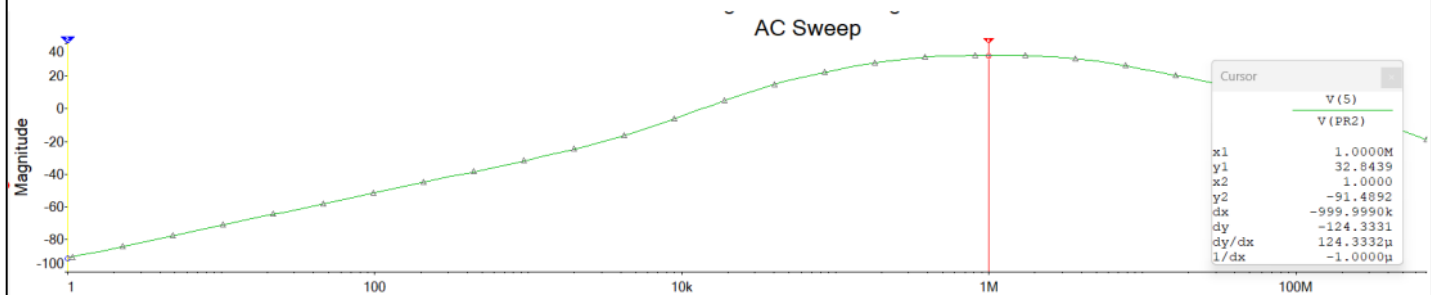


Figure 17 Centre Frequency After Refining the Design

Appendix C: - Improving the Design for Gain

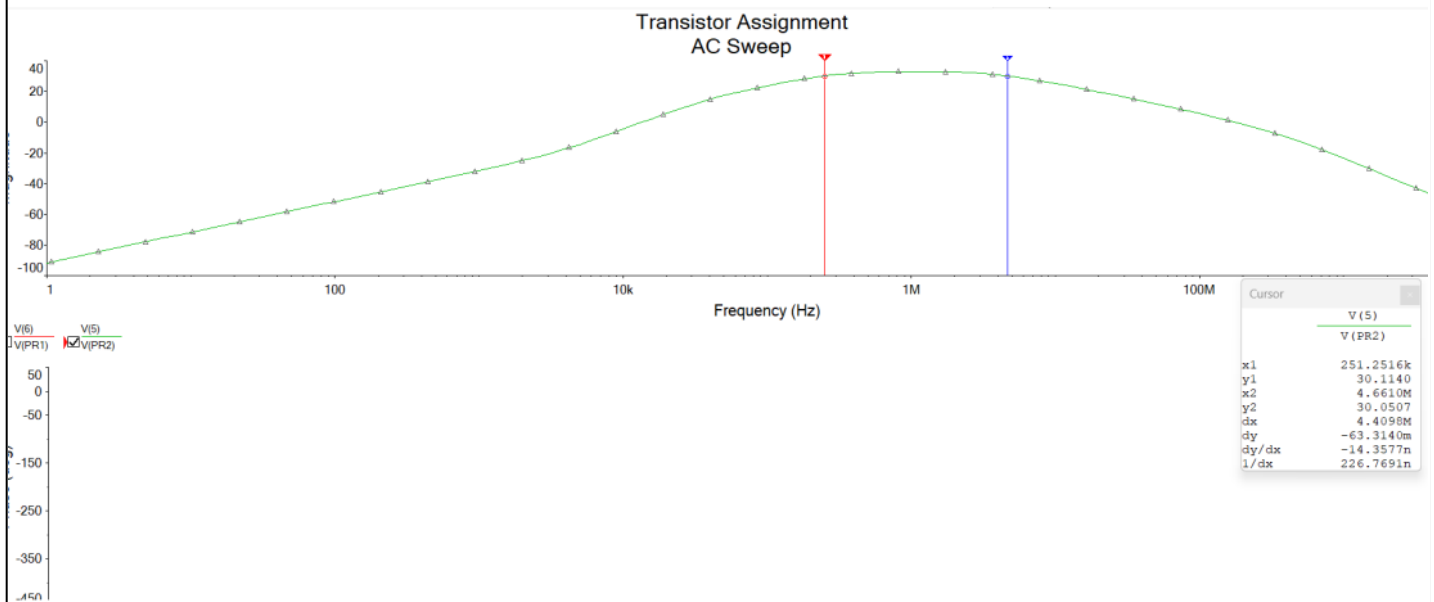


Figure 18 Bandwidth After Introducing Negative Feedback

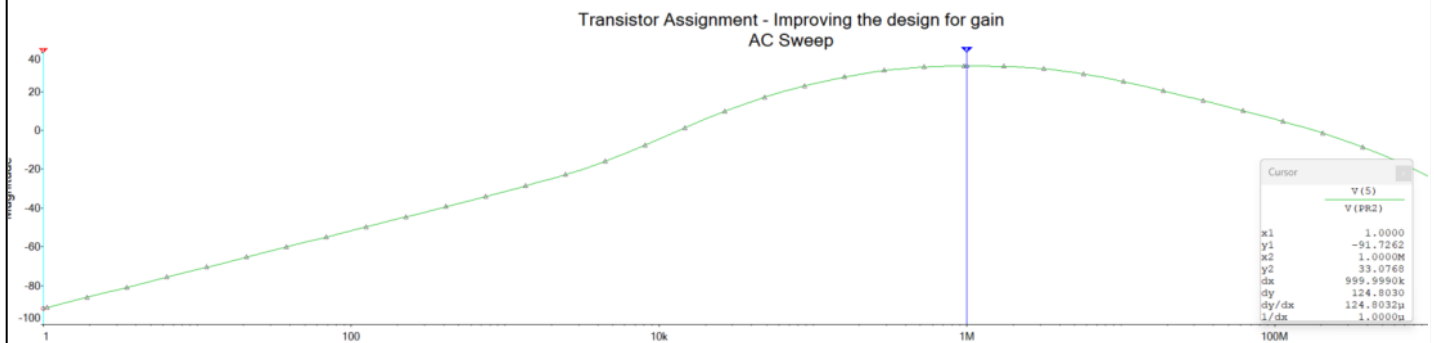


Figure 19 Centre Frequency After Introducing Negative Feedback

Appendix D: - Adding an Oscillator and Building the Final System

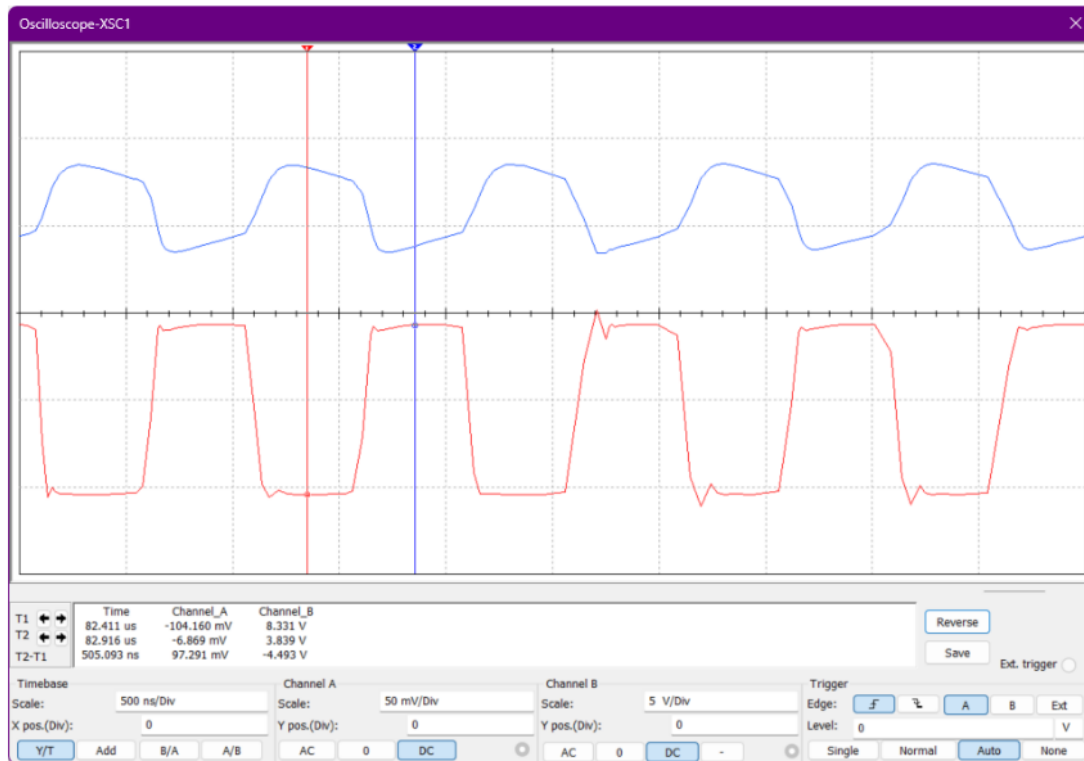


Figure 20 Amplifier Waveform (blue) and Oscillator Waveform (red)

Appendix E: - HFE Value and ICmax Figure

Characteristic	Symbol	Min	Max	Unit
Small-Signal Current Gain ($I_C = 1.0 \text{ mAdc}$, $V_{CE} = 10 \text{ Vdc}$, $f = 1.0 \text{ kHz}$)	h_{fe}	50	200	–
2N3903				
2N3904		100	400	

Figure 21 2N3904 Hfe Value (Semiconductor Components Industries, LLC, 2021)

Collector Current – Continuous	I_C	200	mAdc
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Figure 22 Maximum Collector Current (Semiconductor Components Industries, LLC, 2021)

FINAL GRADE

GENERAL COMMENTS

Instructor

81 /100

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GRADING FORM: CSG-RUBIC

MOHAMMED IBRAHIM

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RESEARCH-INFORMED LITERATURE



There was evidence of extensive further reading and research from credible and reliable sources.

16/20

Your interpretation and understanding of the additional research was very good and demonstrated a deep underlying appreciation of the subject. Your references were consistently applied and appropriate to the task and your reference list was of an appropriate length for this assignment.

KNOWLEDGE AND UNDERSTANDING



The knowledge and understanding of the subject demonstrated by this assignment was generally excellent. There were very few gaps in your knowledge of the basic principles and your understanding of the higher level concepts was demonstrated to a high degree. You have demonstrated a highly competent critical understanding of the main concepts and expanded your knowledge well beyond that contained in the course notes.

17/20

ANALYSIS



Your analysis of the task was excellent, both in class and as shown in this assignment. You have demonstrated highly competent analytical skills and your approach to the task was highly logical. You carried out a detailed evaluation of the results and included an excellent conclusion relating your practical results to accepted theory. You have demonstrated a capacity for independent thought and your interpretation of the quantitative and qualitative data was excellent with sound judgements based on wholly valid arguments.

14/20

PRACTICAL APPLICATION AND DEP.



Your application of practical skills for this task was generally excellent. You used both the basic and advanced features of the resources appropriately when designing the circuit and you used appropriate advanced options for testing and evaluating the circuit performance. You managed to design an effective circuit that functioned well within the specification and achieved this by rarely asking for assistance thus demonstrating some advanced problem solving skills. Your results were comprehensive and allowed for a detailed conclusion to be written.

17/20

SKILLS FOR PROFESSIONAL PRAC.



In this assignment you have demonstrated skills in working individually and also collaboratively. Your written report was written in a professional and confident style, however you still need to be more efficient with your word count. The report was very well presented, with excellent diagrams in appropriate places, good sentence/paragraph structure and clear calculations.

17/20