Analog Lab
Experiment 8: Mixer Circuit

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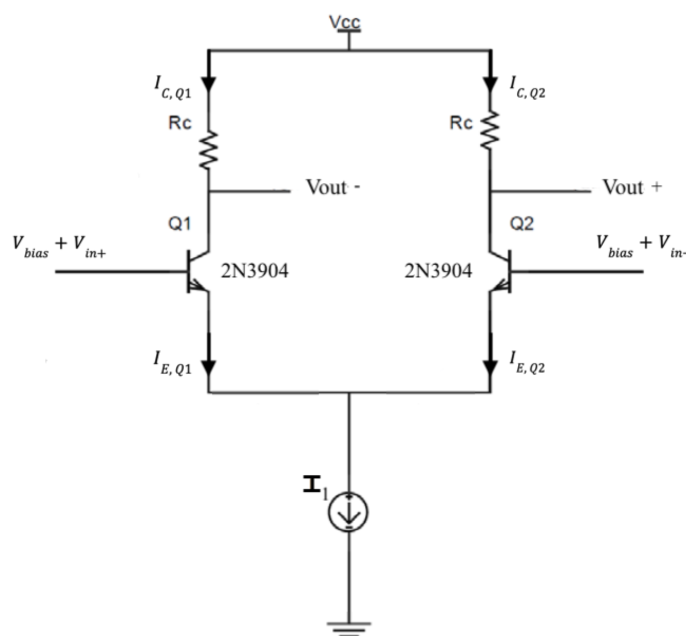
1. **To design a mixer circuit with the following specifications**
   Input signal frequency: 1kHz
   Known periodic signal frequency: 10kHz

   The output of a mixer circuit is the product of the two input signals, and these circuits are heavily used in wireless systems to transmit signals with low frequencies. When we multiply a known periodic signal (high frequency) and a signal with low frequency, convolution occurs in the frequency domain. The resultant signal is centered around the high frequency range, hence this process is called frequency translation. LTI systems cannot perform this and so we need to use the non-linearity property of BJTs and diodes.

   As hinted in the question, we can use the property of BJT that collector current is an exponential function of the base-emitter voltage and using power series expansion we can approximate it as a linear function. So we can use a Gilbert cell which is a type of double balanced mixer and is made using two cross coupled differential amplifiers using BJTs.

   Working of a Differential Amplifier-

   It is a device that amplifies the difference in inputs using BJTs in active mode.



   The two input signals are given at the base of Q1 and Q2 and the output is taken as the difference of the collector voltages.

   I_C and V_{BE} for a BJT are related as follows-

$$I_C = I_S \times exp\left(\frac{V_{BE}}{V_T}\right)$$

   Also I_C and I_E are related as follows-

$$I_C = \alpha I_E$$

   Note that there is a biasing voltage V_{bias} at the input to ensure that V_B is greater than 0.7V for BJT to be in active mode.

Also from KCL: $I_1 = I_{E,Q1} + I_{E,Q2}$

So writing the equations for the two BJTs –

$$I_{C,Q1} = I_S \, exp\left(\frac{V_{bias} + V_{in+} - V_E}{V_T}\right) = \alpha I_{E,Q1}$$

$$I_{C,Q2} = I_S \, exp\left(\frac{V_{bias} + V_{in-} - V_E}{V_T}\right) = \alpha I_{E,Q2}$$

Dividing the above two equations –

$$I_{E,Q1} = I_{E,Q2} \, exp\left(\frac{V_{in+} - V_{in-}}{V_T}\right)$$

Substituting the above result in the KCL equation and taking $(V_{in+} - V_{in-}) \ll V_T$, we can use the power series expansion for e^x and approximate it as $1 + x$. So we get –

$$I_{E,Q1} = \frac{I_1}{2 - \frac{V_{in}}{V_T}} \quad \text{and} \quad I_{E,Q2} = \frac{I_1}{2 + \frac{V_{in}}{V_T}}$$

where $V_{in} = V_{in+} - V_{in-}$ and V_T is the thermal voltage.

Now writing KVL from V_{CC} to V_{out+} and V_{CC} to V_{out-} we get-

$$V_{CC} - I_{C,Q1} R_C = V_{out-}$$

$$V_{CC} - I_{C,Q2} R_C = V_{out+}$$

Subtracting the above two equations and substituting the values for I_C from the above results, we finally get that –

$$V_{out} \approx \frac{\alpha R_C}{2V_T} I_1 V_{in}$$

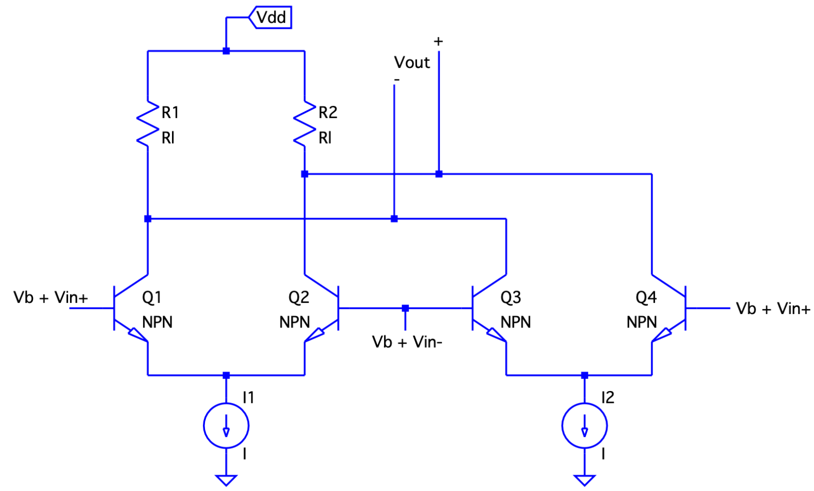
where $V_{out} = V_{out+} - V_{out-}$

In essence the output is the amplified difference between the input signals and can be controlled by changing the constants.

Also note that (this will be useful later) –

$$I_{C,Q1} - I_{C,Q2} = \frac{\alpha I_1}{2V_T} V_{in}$$

The adjacent circuit is a cross-coupled differential amplifier.



Using the superposition theorem, we can find V_{out} as the sum of V_{out} due to differential amplifier 1 (having Q1 and Q2) and differential amplifier 2 (having Q3 and Q4).

So-

$$V_{out} = \left(V_{out}\right)_{diff1} + \left(V_{out}\right)_{diff2}$$

$$V_{out} = \frac{\alpha R_C}{2V_T} I_1 \left(V_{in+} - V_{in-}\right) + \frac{\alpha R_C}{2V_T} I_2 \left(V_{in-} - V_{in+}\right)$$

(using results from above)

$$V_{out} = \frac{\alpha R_C}{2V_T} \left(I_1 - I_2\right) V_{in}$$

Now if we can replace the $I_1 - I_2$ term from the above equation with some voltage, the output will simply be the product of two voltages. Observe that the result from the previous page (last line) does the exact same thing by subtracting the collector currents and equating it to an amplified version of the input voltage. So we can remove the current sources I_1 and I_2 and replace it with another differential amplifier.

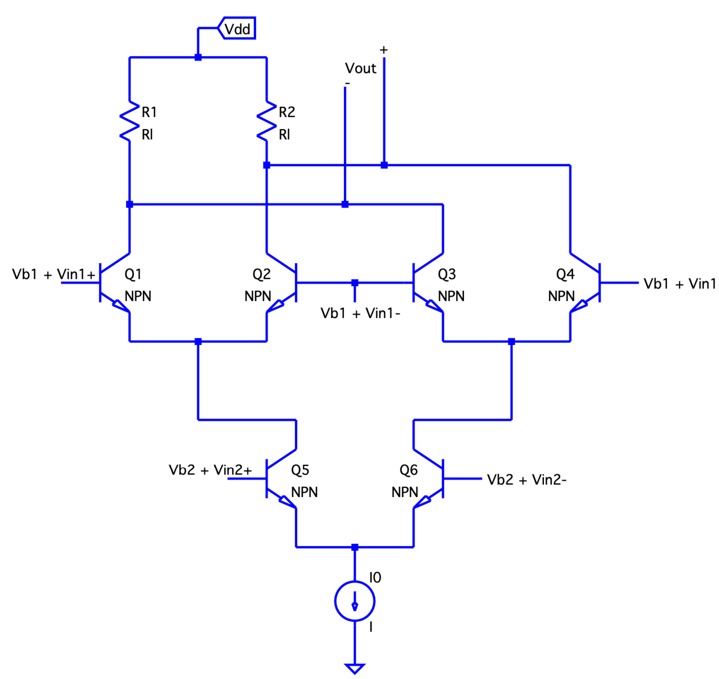
So now in this circuit, we have –

$$I_1 - I_2 = \frac{\alpha I_0}{2V_T} \left(V_{in2+} - V_{in2-}\right)$$

Substituting this back into V_{out} we get-

$$V_{out} = \frac{\alpha^2 I_0 R_C}{4V_T^2} V_{in1} V_{in2}$$

Note that we can always connect the –ve input terminal to GND and +ve input terminal to the input signal if we have a single ended input supply.

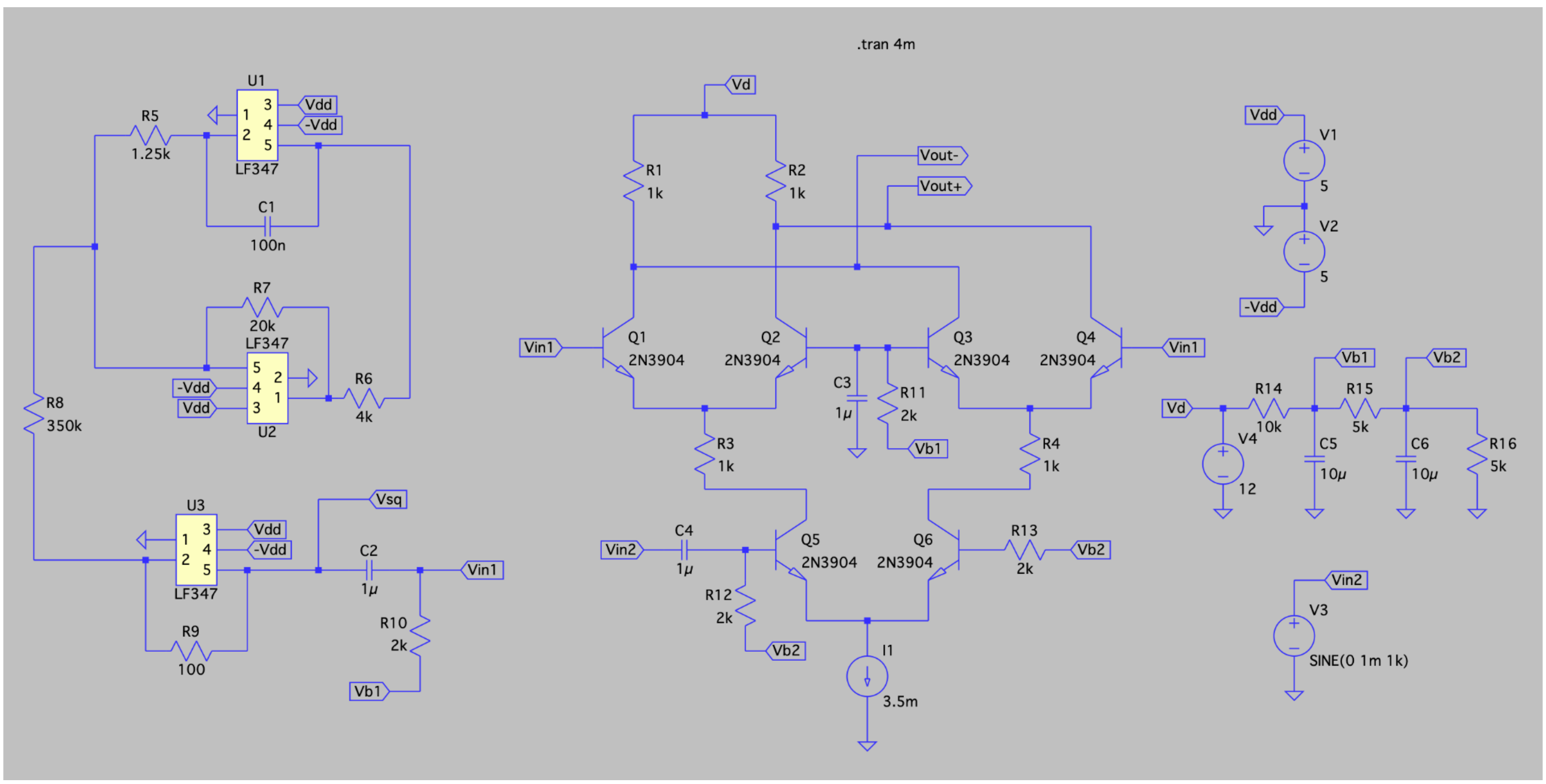


We have used the voltage controlled oscillator from lab 5 but there is a slight modification that we have to scale the voltage down from (-3.5V, +3.5V) to much less than V_T for the circuit to work else the power series approximation will fail. So I have used an op-amp to scale down the voltage range.

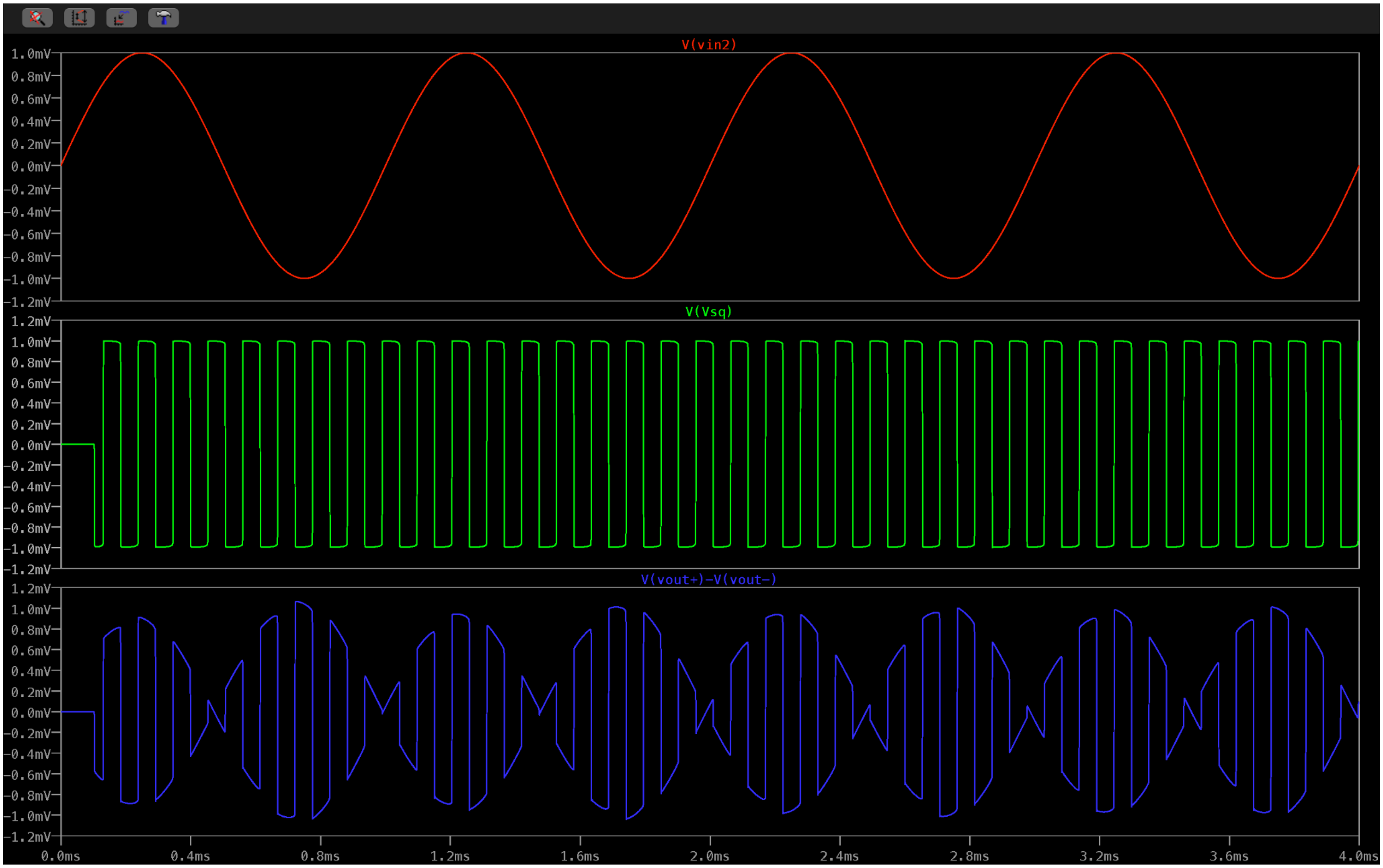
The biasing voltages are generated from the series RC circuit to keep the BJT in active mode of operation. The capacitors are used to remove any sort of noise and also to restrict any DC offset from the signal.

For this experiment, I have chosen R_L as 1kΩ and I_o as 3.5mA. Substituting these values into the gain formula and we get the gain as ~1000.

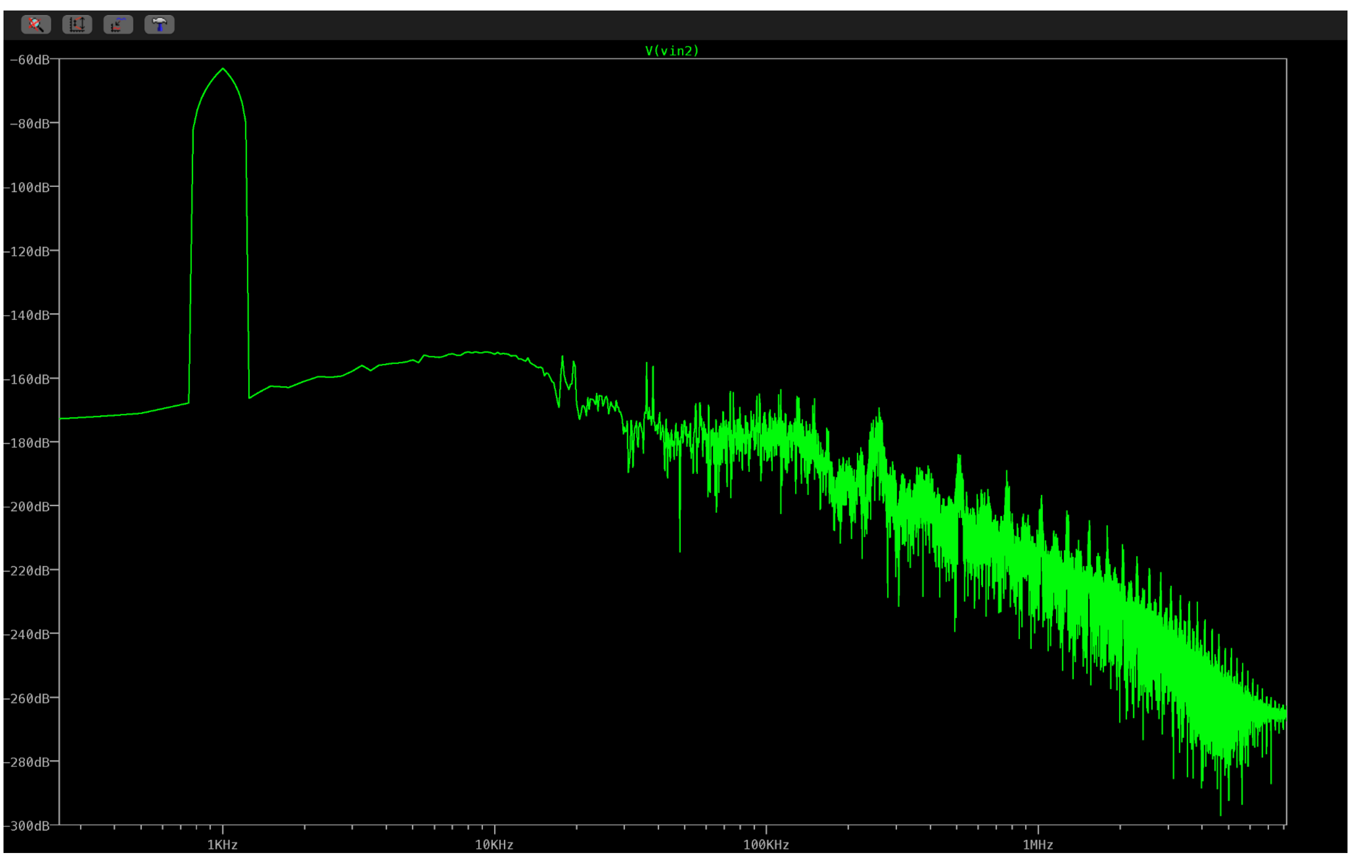
Implementation in LTSpice



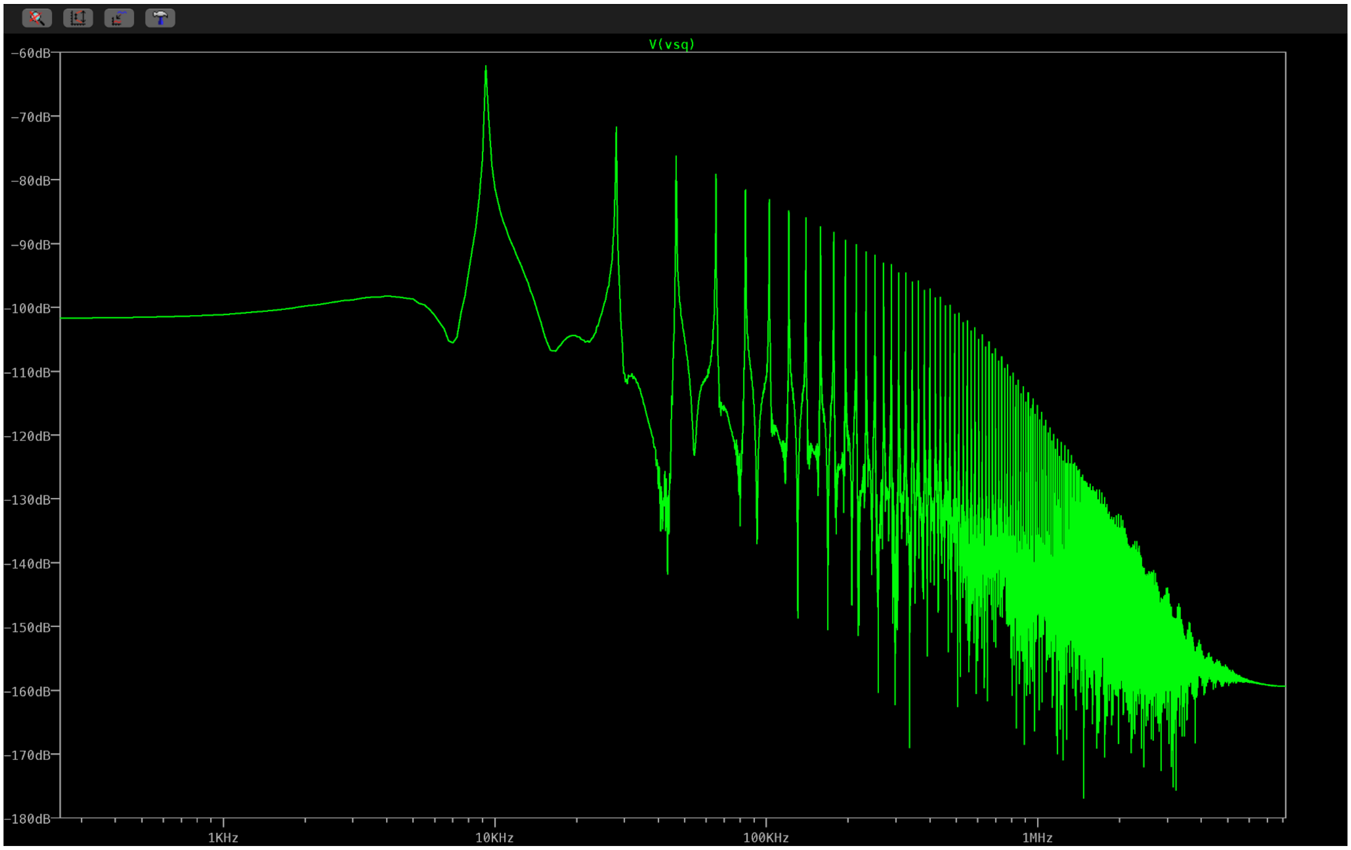
Output Plot-



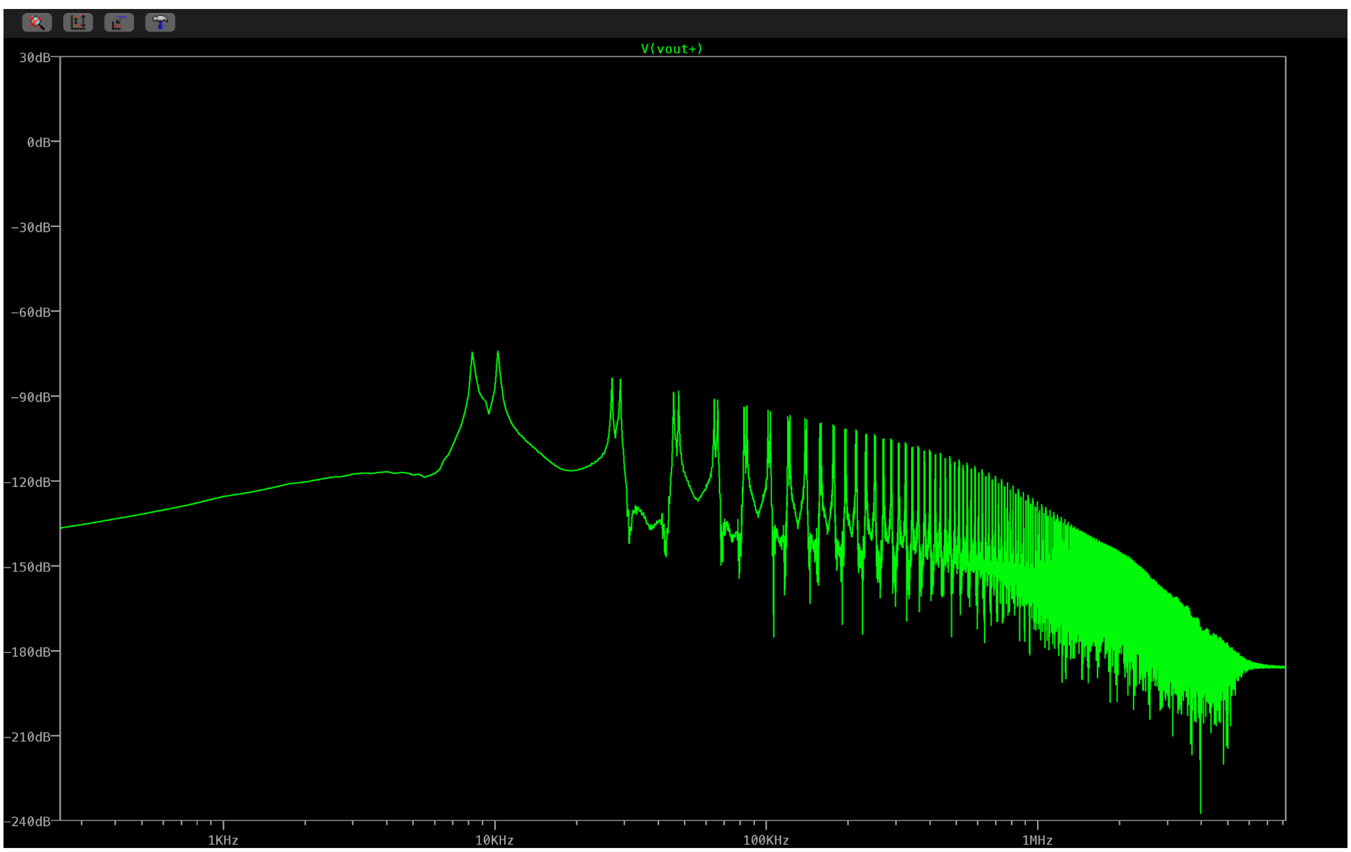
FFT of sinusoid-



FFT of square wave-



FFT of output-



As explained in the start, the low frequency component will be centered around the high frequency component. Clearly there are odd harmonics in the output plot centered around kf_c (k is natural number) and varies in the range $kf_c \pm f_m$ (here f_c is carrier frequency i.e. square wave and f_m is signal frequency i.e. sine wave).

But the shift is not clear at higher frequencies which can be attributed to the imperfections in the square wave or in the BJT.