EEE313 Project Report

Analog Multiplier

Doğa Demirboğa 22101885

Emre Uncu 22003884

Introduction

This project aims to design a multiplier that would multiply two sine waves. A circuit that meets the following specifications was designed using the Gilbert Cell model and BJTs to achieve this.

- 1kHz and 20kHz sine waves as input.
- Dual power supplies (+/- V_{DD}) no more than +/-10V.
- Power consumption should be less than 200mW, i.e., <10mA total current per supply.
- Resistors are allowed.
- A double-balanced mixing cell is required.
- The circuit should generate its own biasing.

Analysis of the Gilbert Cell Model

Analog multipliers are circuits that input two sinusoidal signals and provide an output proportionate to the product of these signals. To begin designing the analog multiplier, it is necessary to figure out the reasoning behind the emitted couple pair. The following figure shows the emitted couple pair.

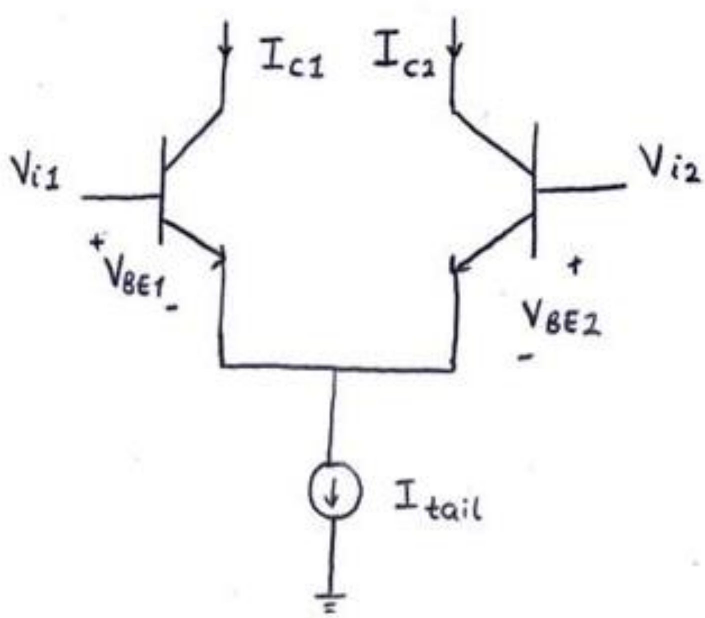

Figure 1: Emitted Couple Pair

Using an emitter-coupled pair, the equation in which the collector current difference is expressed with the output voltage difference is obtained as follows.

First, the diode equation was written for the two collector currents:

$$I_{C_1} = I_S\left(e^{\frac{V_{BE_1}}{V_T}} - 1\right) \quad and \quad I_{C_2} = I_S\left(e^{\frac{V_{BE_2}}{V_T}} - 1\right)$$

$$V_{BE_1} = V_T \ln\left(\frac{I_{C_1}}{I_S}\right) \quad and \quad V_{BE_2} = V_T \ln\left(\frac{I_{C_2}}{I_S}\right)$$

Afterwards, the equation of the voltage difference depending on the collector currents was obtained:

$$V_i = V_{BE_1} - V_{BE_2} = V_T \ln\left(\frac{I_{C_1}}{I_S}\right) - V_T \ln\left(\frac{I_{C_2}}{I_S}\right)$$

$$V_i = V_T \ln\left(\frac{I_{C_1}}{I_{C_2}}\right) \quad and \quad \frac{I_{C_1}}{I_{C_2}} = e^{\frac{V_i}{V_T}}$$

By using the following equation, the collector current difference is expressed with the output voltage difference:

$$-\left(I_{C_1} + I_{C_2}\right) = I_{tail}$$

$$-I_{C_1} = \frac{I_{tail}}{1 + e^{-\frac{V_i}{V_T}}} \quad and \quad -I_{C_2} = \frac{I_{tail}}{1 + e^{\frac{V_i}{V_T}}}$$

$$\Delta I_C = I_{C_1} - I_{C_2} = I_{tail}\left(\frac{1}{1 + e^{\frac{V_i}{V_T}}} - \frac{1}{1 + e^{-\frac{V_i}{V_T}}}\right)$$

$$\Delta I_C = I_{tail}\left(\frac{e^{-\frac{V_i}{2V_T}} - e^{\frac{V_i}{2V_T}}}{e^{-\frac{V_i}{2V_T}} + e^{\frac{V_i}{2V_T}}}\right) = I_{tail}\tanh\left(-\frac{V_i}{2V_T}\right)$$

The Gilbert Cell model was analyzed using the last equation.

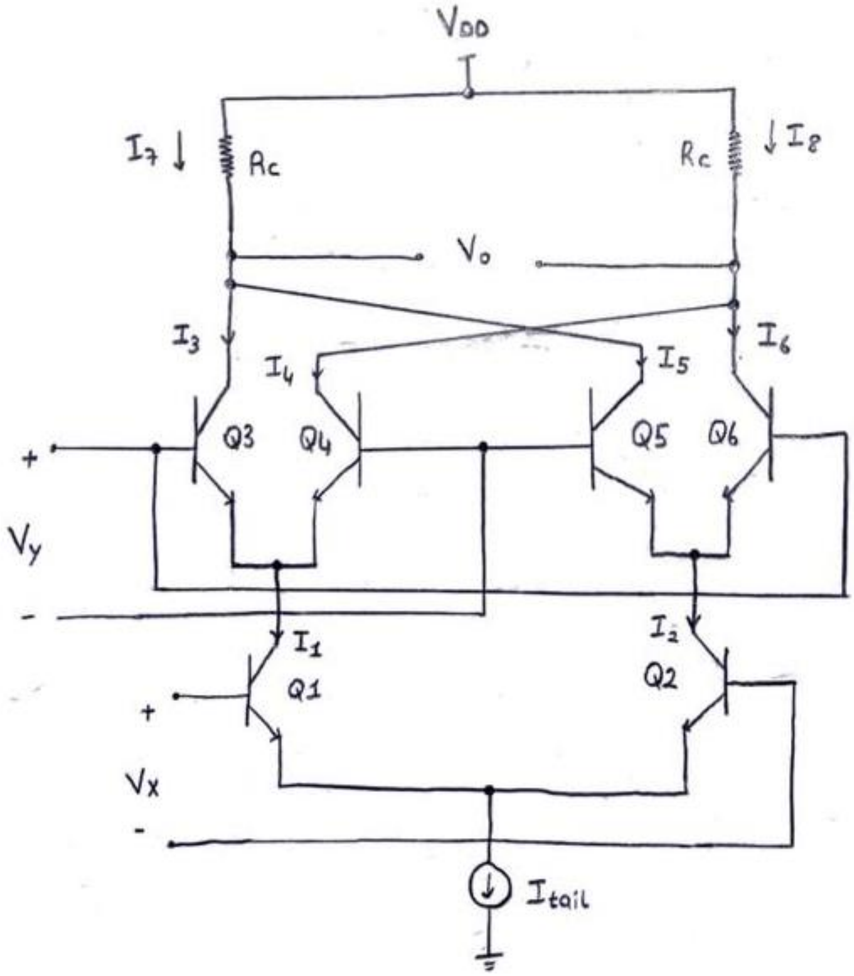

Figure 2: The Gilbert Cell Model

Firstly, the equation obtained above was used for Q3-Q4 and Q5-Q6 BJT pairs, and ΔI_{out} was obtained.

$$I_3 - I_4 = I_1 \tanh\left(-\frac{V_y}{2V_T}\right) \quad and \quad I_6 - I_5 = I_2 \tanh\left(-\frac{V_y}{2V_T}\right)$$

$$\Delta I_{out} = I_7 - I_8 = (I_3 + I_5) - (I_4 + I_6) = (I_3 - I_4) - (I_6 - I_5)$$

$$\Delta I_{out} = I_1 \tanh\left(-\frac{V_y}{2V_T}\right) - I_2 \tanh\left(-\frac{V_y}{2V_T}\right) = (I_1 - I_2) \tanh\left(-\frac{V_y}{2V_T}\right)$$

$$I_1 - I_2 = I_{tail} \tanh\left(-\frac{V_x}{2V_T}\right)$$

$$\Delta I_{out} = I_{tail} \tanh\left(-\frac{V_x}{2V_T}\right) \tanh\left(-\frac{V_y}{2V_T}\right)$$

$$Assuming \quad V_x < 2V_T \quad and \quad V_y < 2V_T$$

$$\Delta I_{out} = \frac{I_{tail}}{4{V_T}^2} V_x V_y$$

$$V_o = R_C \Delta I_{out} = \frac{R_C I_{tail}}{4{V_T}^2} V_x V_y$$

As a result of the operations performed as seen above, $V_o = K * V_x V_y$, that is, an output voltage proportional to the product of the input voltages was obtained, thanks to the Gilbert Cell.

Software

The analog multiplier circuit created using Gilbert Cell is as follows:

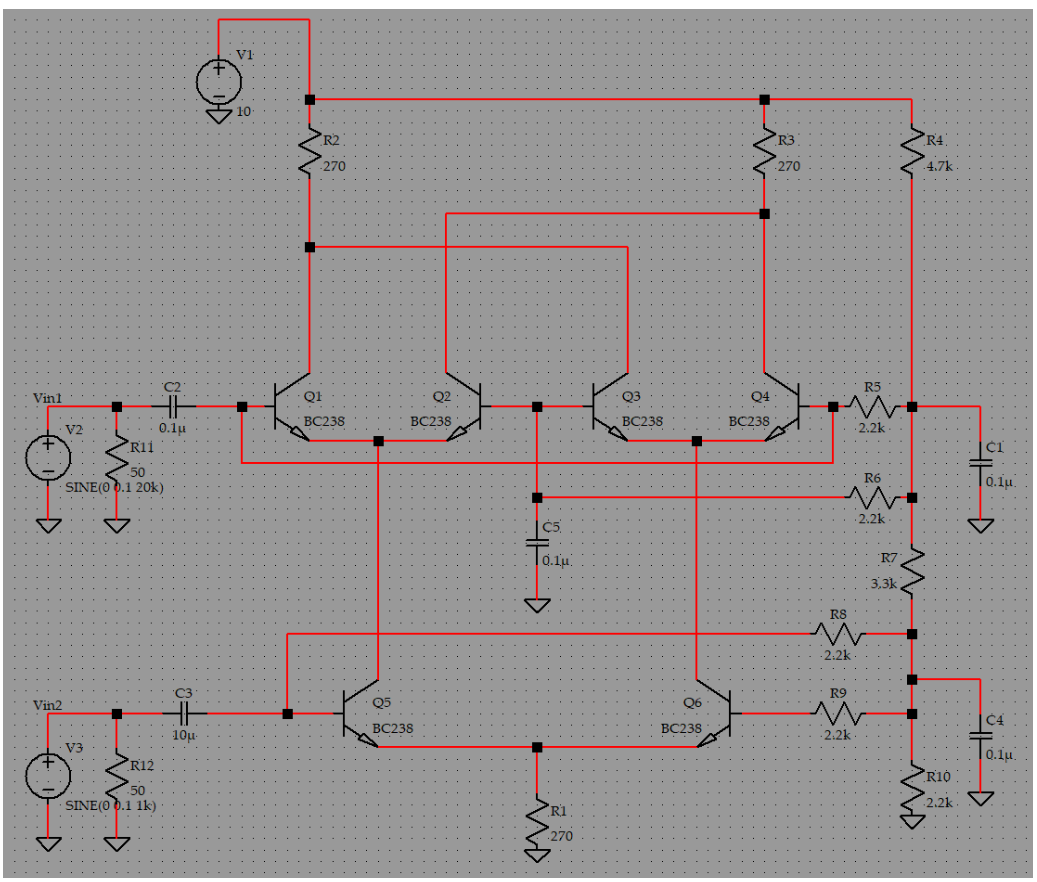

Figure 3: The Gilbert Cell Model

The figure below shows 0.1 V 1kHz and 0.1 V 20kHz input voltages and the output voltage obtained as their product.

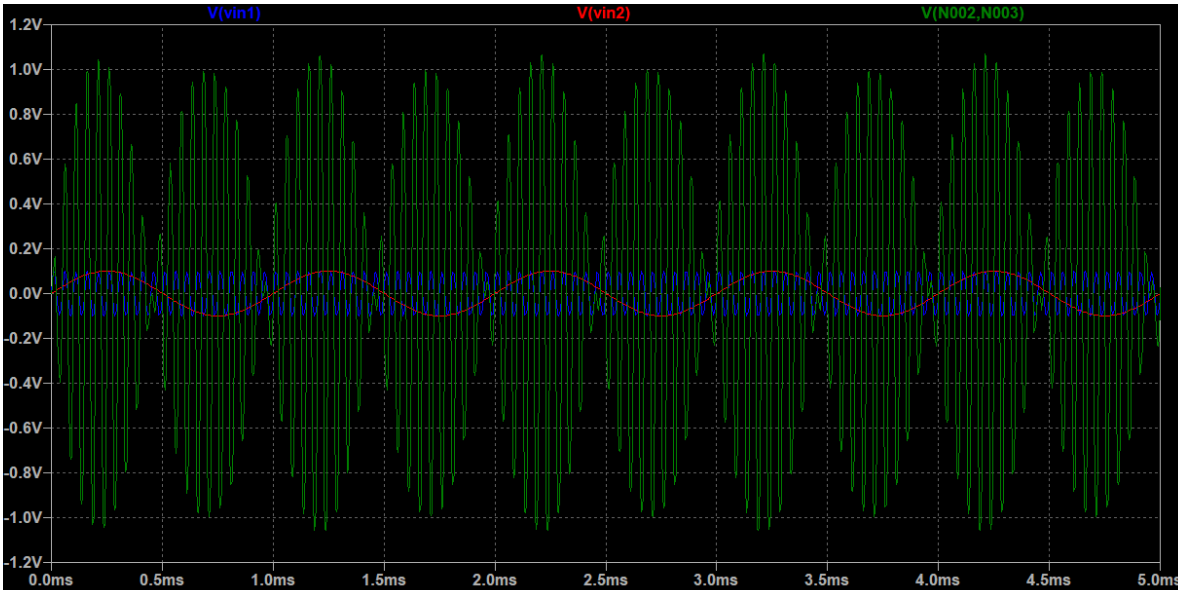

Figure 4: Input Voltages and Output Voltage

To observe the saturation, the measurement was repeated when the input voltages were 0.3V and 0.5V.

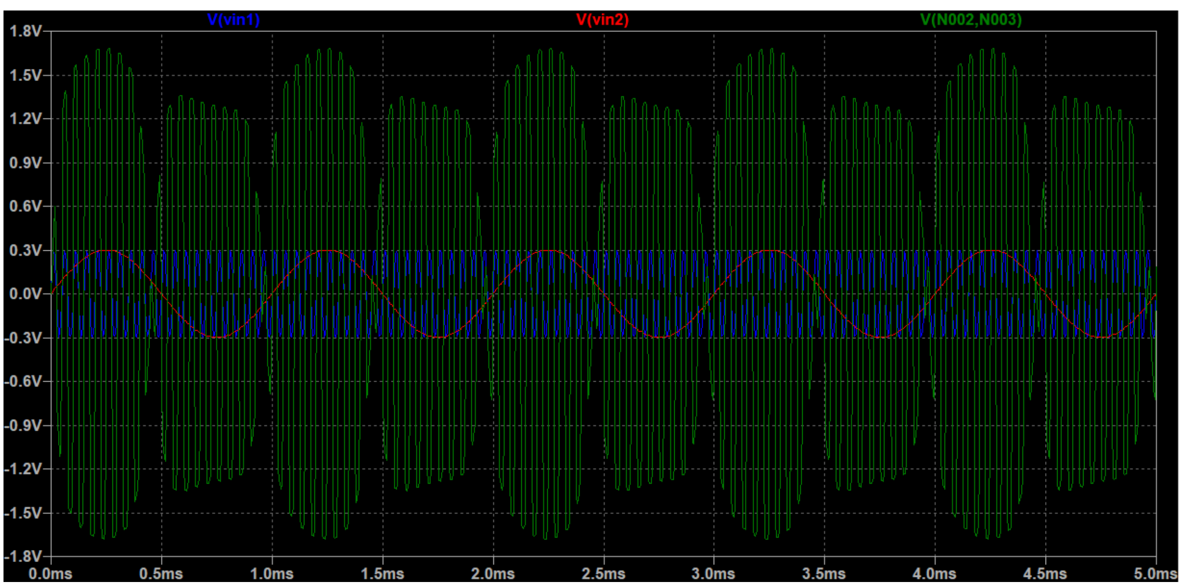

Figure 5: Input Volotages at 0.3V

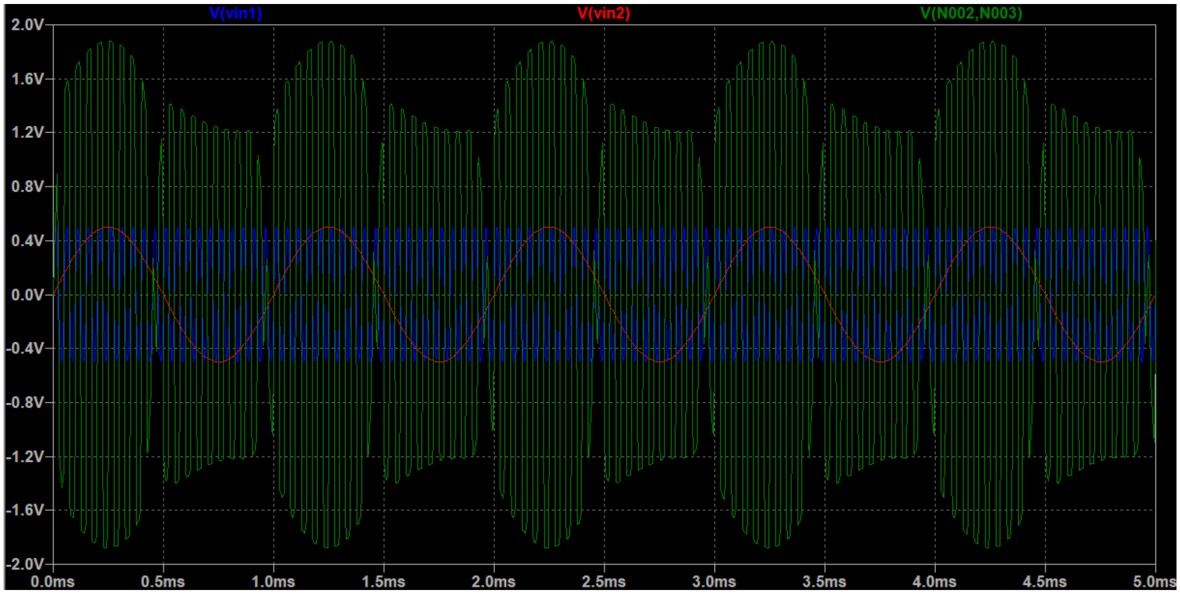

Figure 6: Input Volotages at 0.5V

When the input voltages were increased, the size of the AM-modulated signal increased, and its shape was distorted, so saturation was observed.

The power consumption plot for the 10V DC supply is as follows:

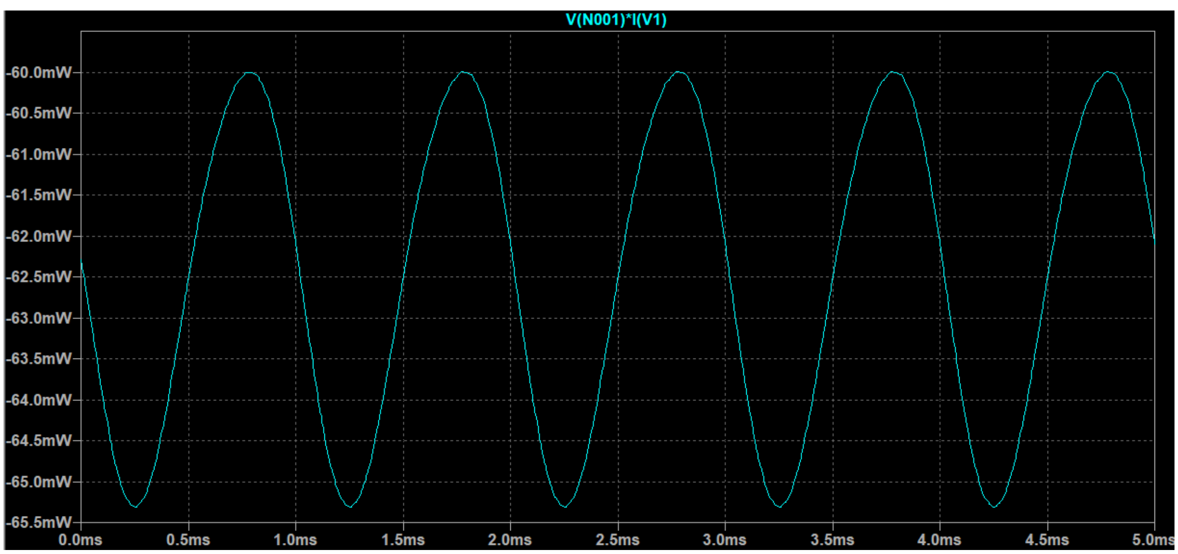

Figure 7: The Power Consumption Plot For DC Supply

As can be seen, power consumption is less than 200 mW and meets the specifications.

Hardware

In this part, the same circuit established in LTSpice is installed on the breadboard as follows:

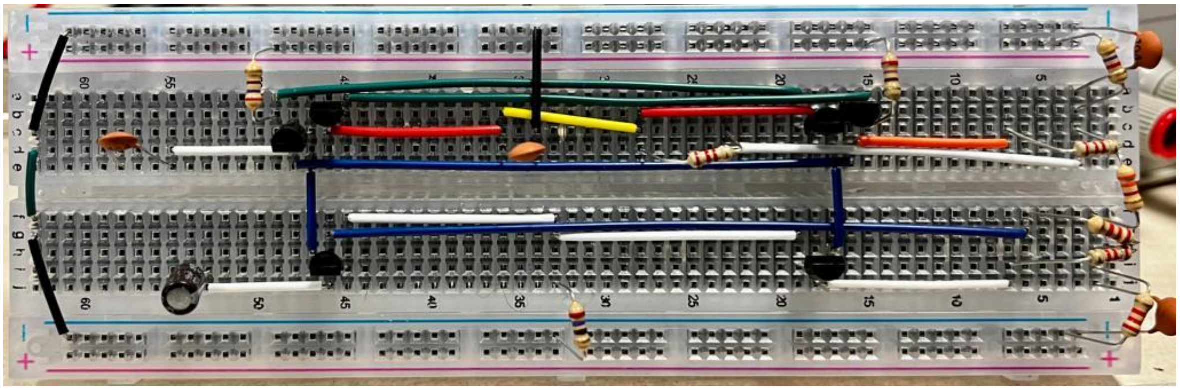

Figure 8: The Breadboard Implementation

1 kHz and 20 kHz input voltages and 10V DC supplied to the circuit are as follows:

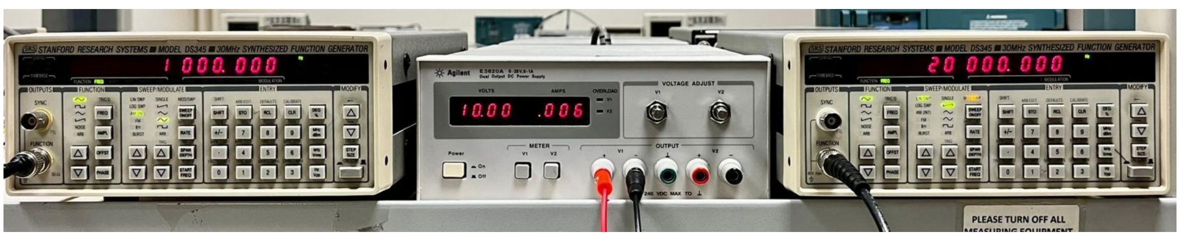

Figure 9: DC and AC Inputs

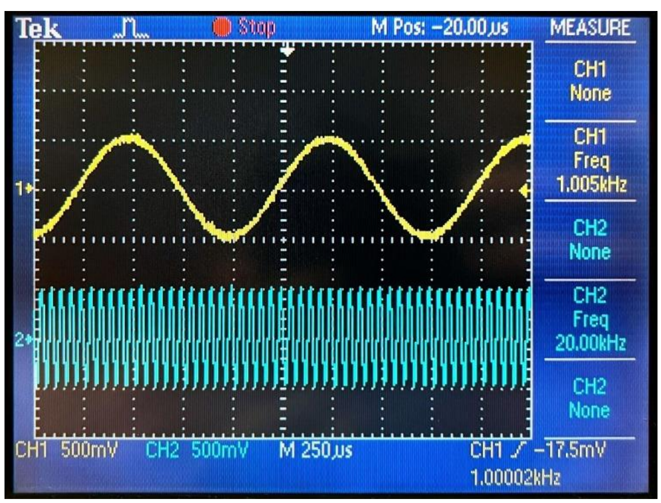

Figure 10: AC Inputs

Additionally, as seen in Figure 9, when 10V is supplied from the DC supply, the power consumption value is measured as $6 * 10 = 60\, mW < 200\, mW$ that satisfies the specifications.

The images of AM modulated output on the oscilloscope are as follows:

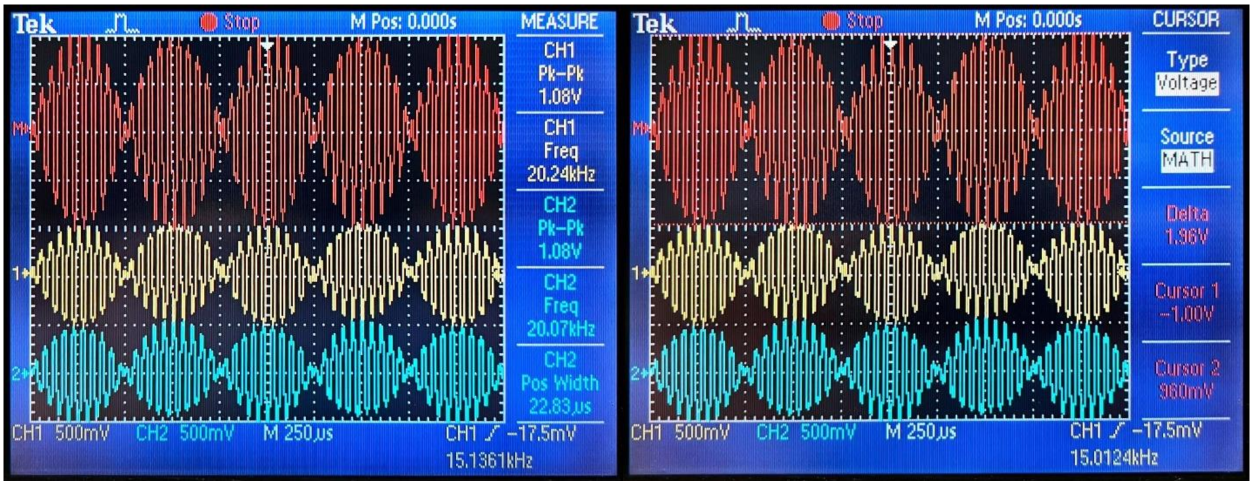

Figure 11:Measurements of the Output signal (red)

In the software section, distortions in shape and saturation were observed as the input voltages increased. Likewise, measurements were repeated by increasing the sinusoidal inputs in the hardware from 0.1V to 0.3V and 0.5V, and saturation was observed, as seen in the photographs.

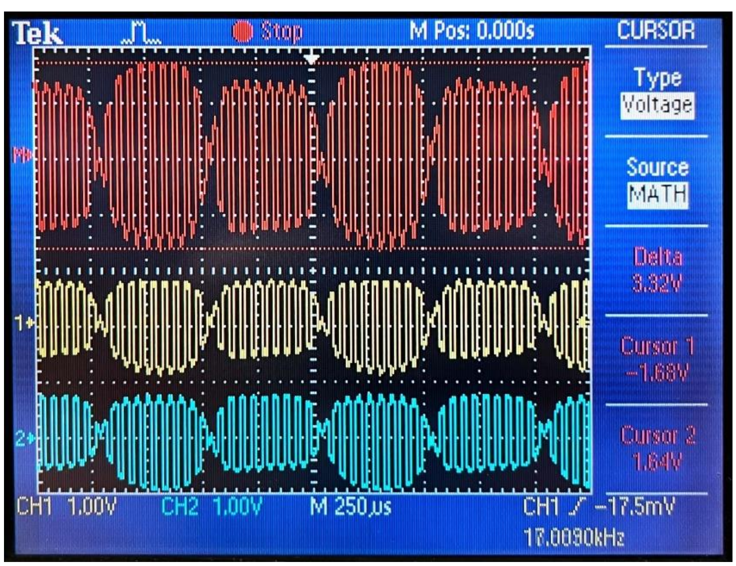

Figure 12: Measurements of the Output signal (red) at 0.3V Inputs

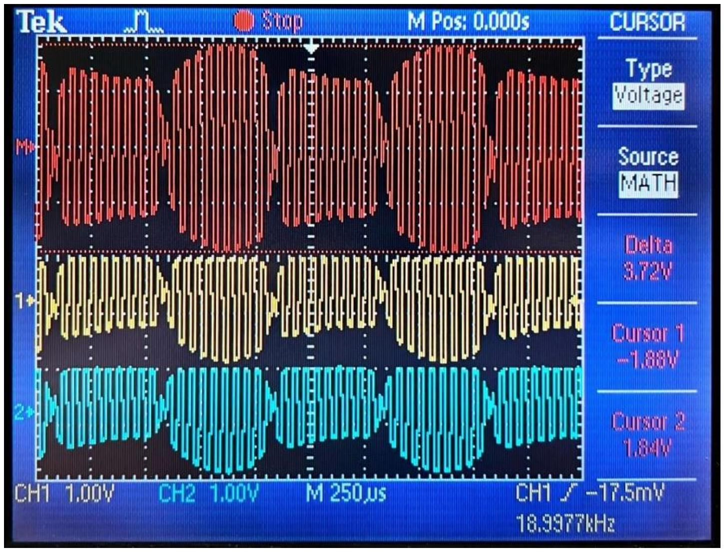

Figure 13: Measurements of the Output signal (red) at 0.5V Inputs

For the next step, FFT analysis of the output signal was performed, and the frequency contents were examined; the following figure shows the FFT analysis at 0.1V input:

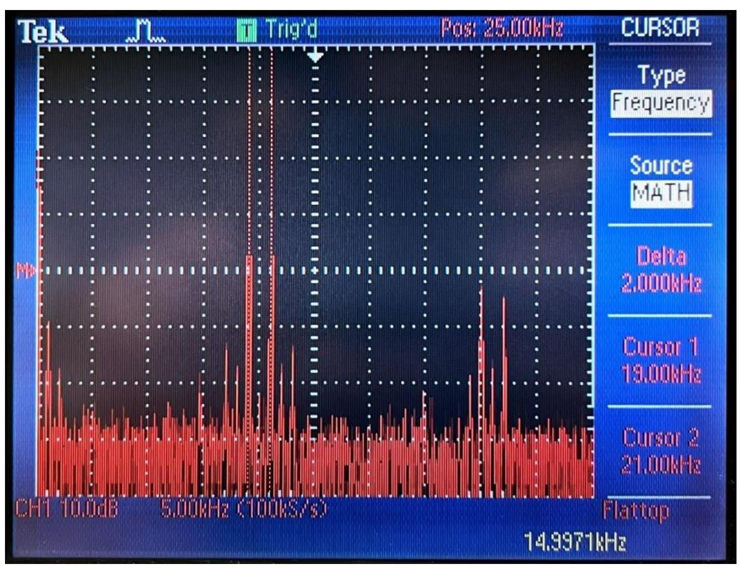

Figure 14: FFT Analysis at 0.1V Input

In Figure 14, two impulses centered on 20kHz appeared, as expected. This verifies that the signal has been successfully modulated at 20kHz.

As the input amplitude increased, saturation was observed. As expected, this saturation also causes distortions in the frequency domain. The figures below show FFT analysis when the input is increased to 0.3V and 0.5V, respectively:

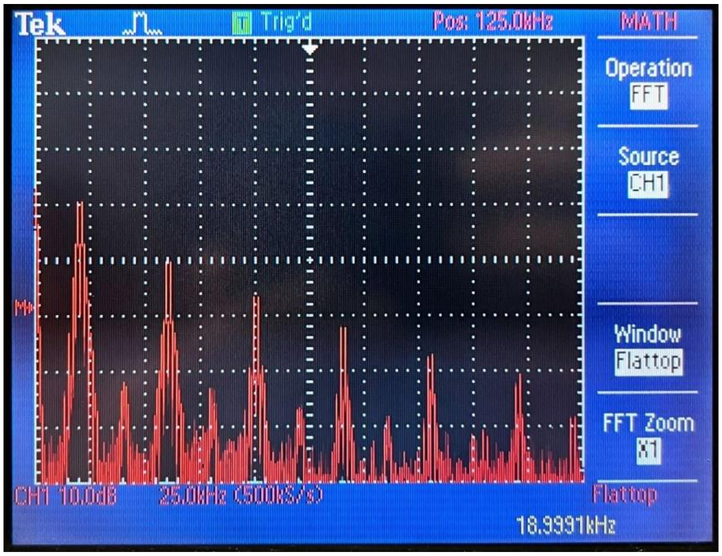

Figure 15: FFT Analysis at 0.3V Input

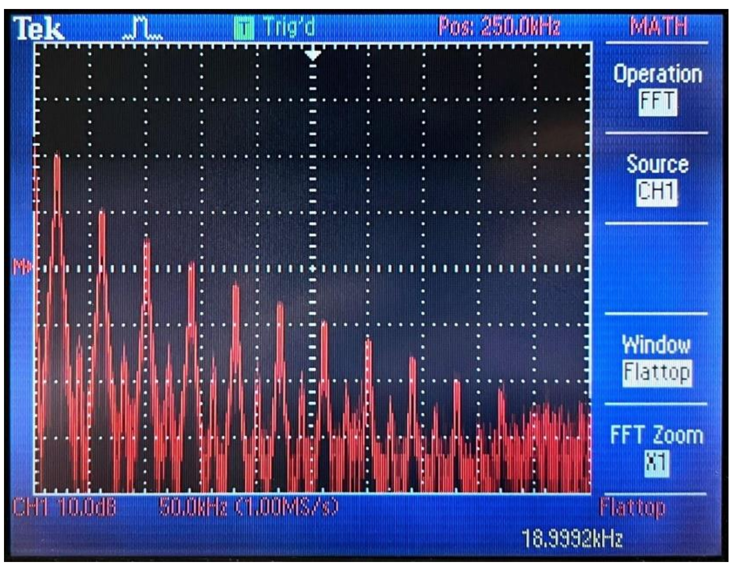

Figure 16: FFT Analysis at 0.5V Input

These distortions cause more impulses to be seen in the frequency domain due to the periodicity of the inputs. In addition, it has been observed that the impulse magnitudes in the saturated image gradually decrease.

Conclusion

This lab aimed to design a circuit that multiplies two analog signals. The Gilbert Cell Model was used to achieve this goal. Primary research on differential amplifiers and a deep analysis of the Gilbert Cell Model was done. After the research part, the circuit was set in LTSpice to observe the results. The resistor values were determined by the trial and error method. After determining every value in the software, the circuit was implemented on the breadboard very neatly and similarly to the LTSpice circuit to find where to look quickly if there was any problem. The transistors were worked with carefully, and efforts were made to avoid burning any circuit elements.

There were no significant difficulties during the lab. Some minor errors occurred due to the non-ideal BJT, imprecise component values, and the material quality or sensitivity of the oscilloscope, signal generator, multimeter, and breadboard. However, none of the errors prevented meeting the project assignment's specifications.

This project was beneficial for understanding how to deal with analog signals and how to make nonlinear operations with them. Complex circuit analysis was essential for understanding differential amplifiers and the Gilbert Cell model. Thanks to this project, the abilities in designing and analyzing electronic circuits were increased, especially circuits containing BJTs and transistors.

Reference

Nigam. Anurag, "Advanced RF designs using ADS-part II - ppt download," SlidePlayer, https://slideplayer.com/slide/12017997/ [Accessed: Jan. 3, 2024].