Quadrature Down Converter

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***Abstract*— In contemporary communication architectures, data is transmitted using high-frequency signals. At the reception stage, these signals are transformed into lower frequency counterparts to facilitate further processing. A pivotal component in this conversion process is the Quadrature Down Converter (QDC), which plays a critical role in mobile communication systems. This project aims to design and implement a rudimentary version of a QDC, exploring its foundational principles and evaluating its performance within a simulated mobile communication environment.**

Keywords— **Quadrature Down Converter (QDC), Switch, low-pass filter.**

I. Introduction

This project aims on constructing a quadrature down oscillator using a oscillator, switch and a low pass filter and adjusting the practical circuit in the lab. down converters are used often to convert the radio frequency signals to the required intermediate frequency signals. A QDC converts a high-frequency input signal into two low-frequency signals with a phase difference of 90o.

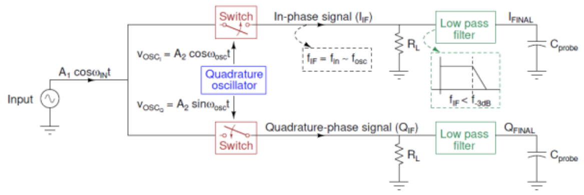

Fig. 1. Reference circuit diagram for QDC

The design presented has the following main components:

1) Quadrature Oscillator: The oscillator generates two sinusoids with a phase difference of 90^o, These sinusoids will control our two switches.
The final outputs are of the form -
vIFI =A1A2/2(cos(ωint−ωOSCt)+cos(ωint+ωOSCt)) (1)
vIFQ =A1A2/2(sin(ωint+ωOSCt)−sin(ωint−ωOSCt)) (2)
2) Switch (Mixer): The switch is realized using MOSFETs. It is used to multiply the signal at the source of the MOSFET with a square wave. A detailed discussion is covered in the next section.
3) Low Pass Filter: The output of the switch is passed through a low pass filter to get rid of all the high-frequency components.

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II. SWITCH(MIXER)

When the gate of the MOSFET is biased close to its threshold voltage, it operates in the linear region. In this region, the MOSFET acts as a resistor, and the resistance between the source and drain terminals is controlled by the voltage applied to the gate. During the positive half of the gate signal, the MOSFET is in linear mode, allowing current to flow from the source to the drain. During the negative half of the gate signal, the MOSFET is in cutoff mode, effectively blocking current flow between the source and drain. The output of the switch is equivalent to multiplying the input signal at the source of the MOSFET with a square wave. This multiplication process is achieved due to the switching action of the MOSFET controlled by the gate signal. When the MOSFET is in the linear region, the input signal can pass through. When it is in cutoff mode, the input signal is effectively blocked.
When a signal is transmitted, it is first modulated to avoid the effect of noise while communicating over larger distances.
This signal when received at the receiver needs to be demodulated to get the original signal.
The signals generated from the oscillator are of the form cosA and sinA, while considering the input signal to be of the form cosB.
∴ The multiplied signals are of the form cosAcosB and sinAcosB.
∵ The input signal is multiplied with a square wave. The fourier series of a square wave of frequency ω can be represented as :

$$\frac{4}{\pi}\sum_{n=1,3,5,..}^{\infty}\frac{1}{n}sin\left(\frac{2n\pi x}{\omega}\right)$$ ....(1)

∴The output of the switch can be expressed as follows:
sinB · f (x).... (1) ,where
f(x) = 1,0 ≤ t ≤ ω/2
f(x) = 0,ω/2 < t ≤ ω
f(x) can be represented by its fourier series and the above equation can be written as :

$$sinB \cdot \frac{4}{\pi}\sum_{n=1,3,5,..}^{\infty}\frac{1}{n}sin(\frac{2n\pi x}{\omega})$$

To filter out the higher frequency components from this output signal, the signal is passed through a low pass filter in the next stage. We can write these signals as :

$$cosAcosB = \frac{1}{2}\cdot((cos(A-B)-cos(A+B))$$

$$sinAcosB = \frac{1}{2}\cdot((sin(A+B)+sin(A-B))$$

The desirable output or the original signal before modu- lation will be obtained from the terms cos(A-B) and sin(A- B). These 2 signals can be filtered from the other 2 signals by passing through a low-pass filter. The above signals of desirable frequency are generated by passing the input signal and the signals from the quadrature oscillator through the switch(mixer).
The purpose of including the capacitor Cc is to AC couple the signal generated by the oscillator. The resistor (RBIAS) ensures that the gate of the MOSFET is not directly connected to AC ground in the small signal model.
A high RBIAS is necessary to avoid the flow of a very high small signal current through the bias resistor. Now, in the small signal model, CC and RBIAS form a high pass filter. So, the value of CC should be high enough to allow a signal of 100kHz to pass conveniently.

∴ The values we have chosen for our circuit are:

C_c = 10uF
$R_{BIAS} = 120k\Omega$

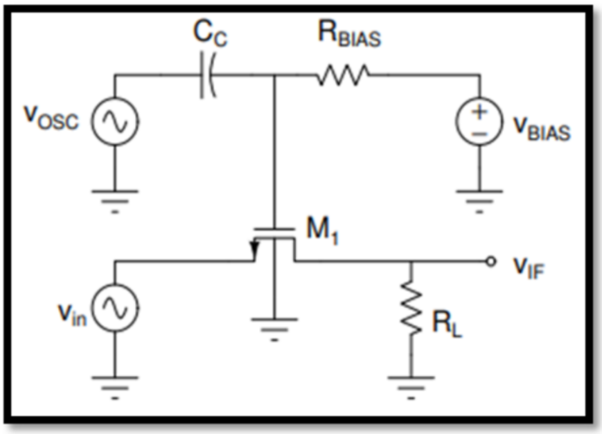

Fig. 2. Reference circuit diagram for Switch

Multiplication of a square wave (which is controlled by the oscillator signals) and V_{IN} is the desired output of the mixer. The signal produced by the quadrature oscillator is such that for sinA > 0 and cosA > 0, where sinA and cosA are the signals produced by the quadrature oscillator; the switch is driven into the linear or triode region, =⇒ in this condition, the switch acts as a resistor and a 'high' output is generated such that f(x) = 1, where f(x) is the same as mentioned in equation (1).

For values of sinA and cosA < 0, the switch is driven into the cutoff mode, hence producing a 'low' output such that f(x) = 0.

V_{OSC} or the signal generated by the oscilloscope has an amplitude of 500 mV and a frequency of 100 kHz.

CALCULATION OF VT

For an NMOS in cutoff -

$VGS < VT$

and in saturation -

$VGS \geq VT$, $VDS < VGS - VT$

$vgs = vosc - vin$

$iD = \mu NCOX(W/)L((vgs - VT)vDS - v\text{^}2DS/2)$

To get the specified ideal amplitude (vif = 25mV), forthe resistor to block AC and for the capacitor to block DC and act as a short for AC -

$vOSC(\omega RBIASCC)/1 + \omega RBIASCC \approx 0$

$\omega RBIASCC >> 1$

$\omega >> 1/RBIASCC$

Hence for RBIAS = 120kΩ, CC ≈ 10μF

VBIAS = VGS and for the edge of cutoff, VGS = VT

Hence -VBIAS = VT , VT ≈ 0.5V

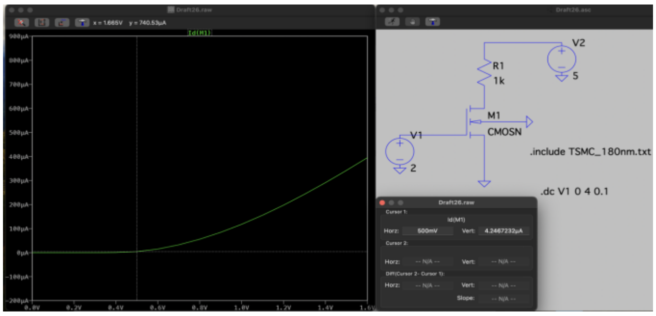

Fig. 3. Calculating Vt

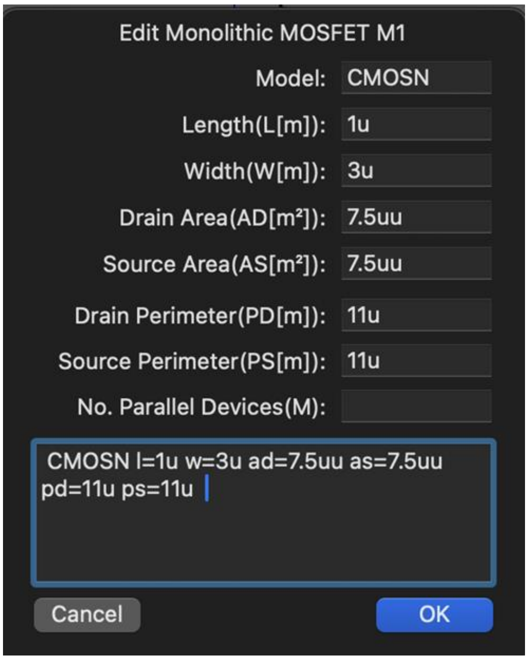

Fig 4. MOSFET Parameters

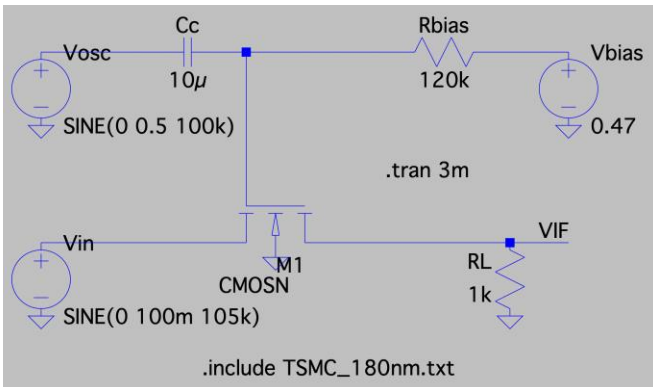

Fig. 5. LTSpice simulated circuit for switch (mixer)

The following is the output observed for the switch:

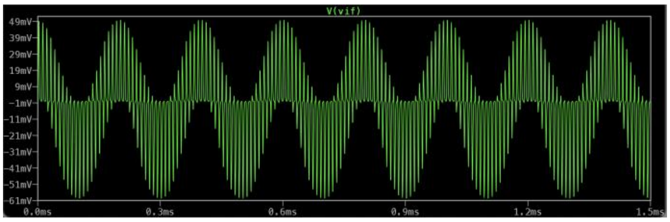

Fig. 6. Output (V_{IF}) of Switch

The outputs observed are for a fixed input wave but different V_{OSC} . The plot illustrates that multiple sinusoidal waves are enveloped under a sinusoidal wave of frequency of approximately 160 Hz. These multiple sinusoidal waves are the result of multiplication of the fourier series components of the square wave which had multiple frequencies as shown in the equation above (eqn (1)). To filter out the required frequencies from these multiple sinusoidal waves, we require the LPF.

The plots for different oscillator frequencies and their corresponding FFTs are shown below:

1) 95kHz:

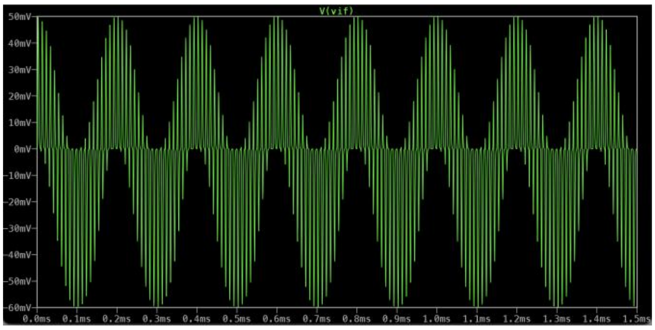

Fig. 7. Output (V_{IF}) of Switch for Vin = 95 kHz

The corresponding FFT plot :

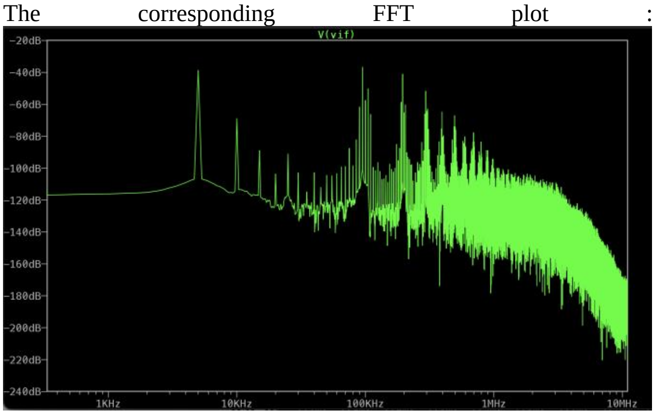

Fig. 8. FFT of Output (V_{IF}) of Switch for V_{OSC} = 95 kHz

Fig. 9. FFT of Output (V_{IF}) of (Implemented) Switch for V_{OSC} = 95 kHz

2) 98kHz

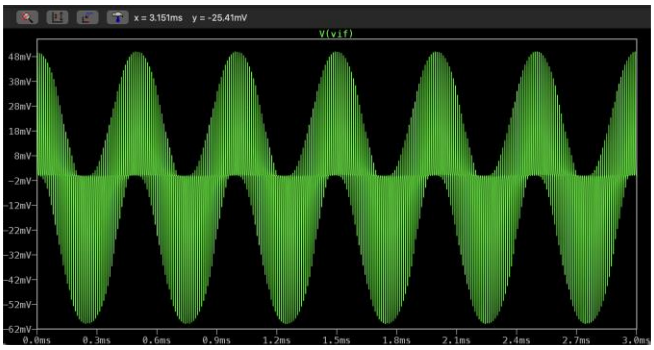

Fig. 10. Output (V_{IF}) of Switch for Vin = 98 kHz

The corresponding FFT plot :

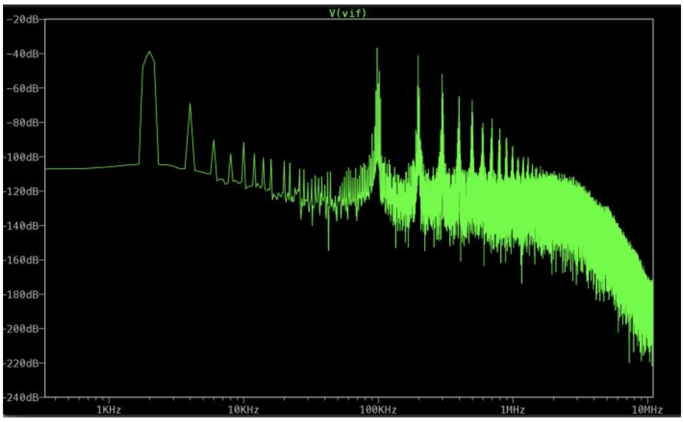

Fig. 11. FFT of Output (V_{IF}) of Switch for V_{OSC} = 98 kHz

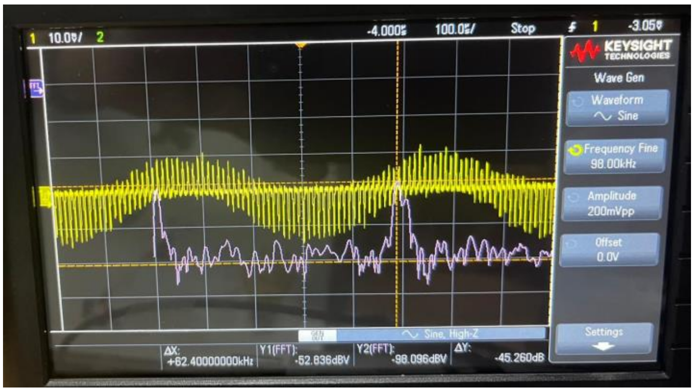

Fig. 12. FFT of Output (V_{IF}) of (Implemented) Switch for V_{OSC} = 98 kHz

3) 99kHz

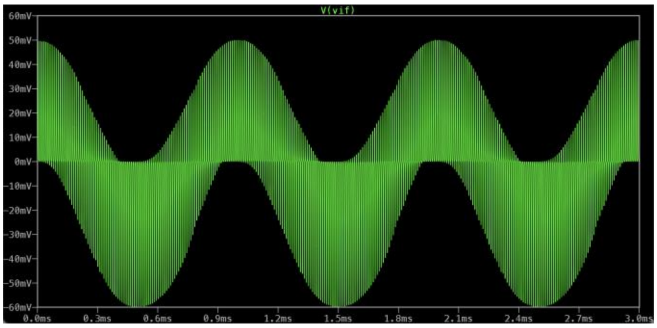

Fig. 13. Output (V_{IF}) of Switch for Vin = 99 kHz

The corresponding FFT plot :

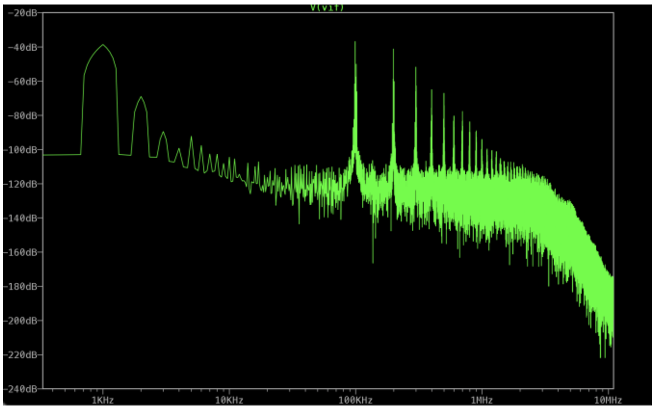

Fig. 14. FFT of Output (V_{IF}) of Switch for V_{OSC} = 99 kHz

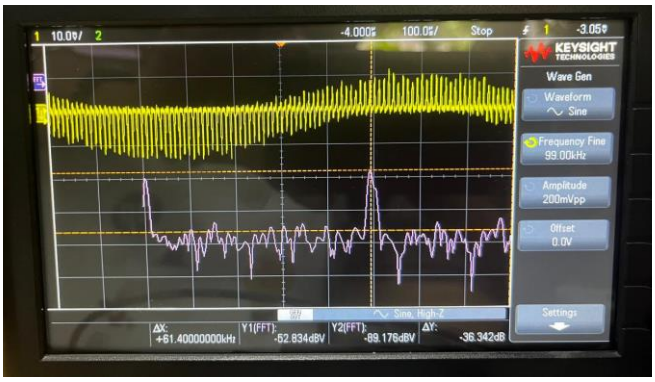

Fig. 15. FFT of Output (V_{IF}) of (Implemented) Switch for V_{OSC} = 99 kHz

4) 101kHz

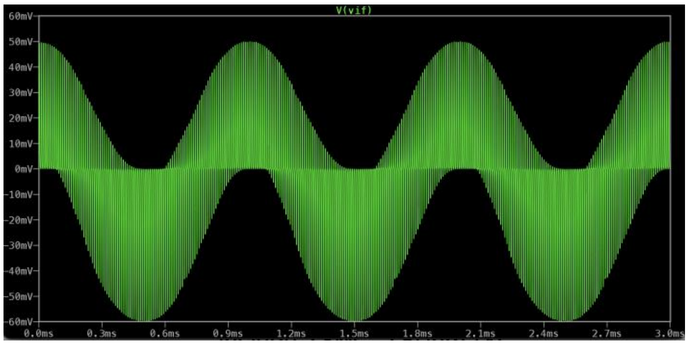

Fig. 16. Output (V_{IF}) of Switch for Vin = 101 kHz

The corresponding FFT plot :

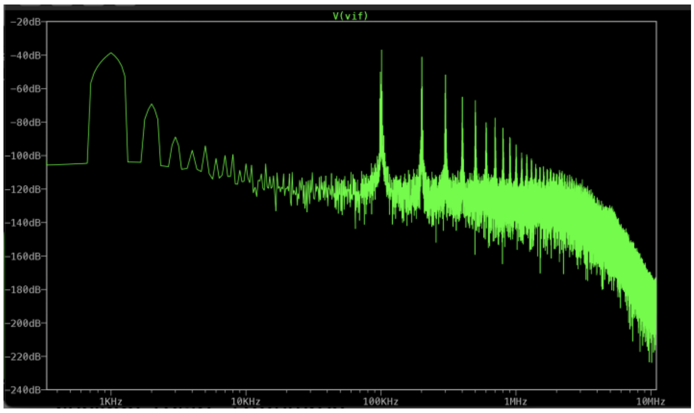

Fig. 17. FFT of Output (V_{IF}) of Switch for V_{OSC} = 101 kH

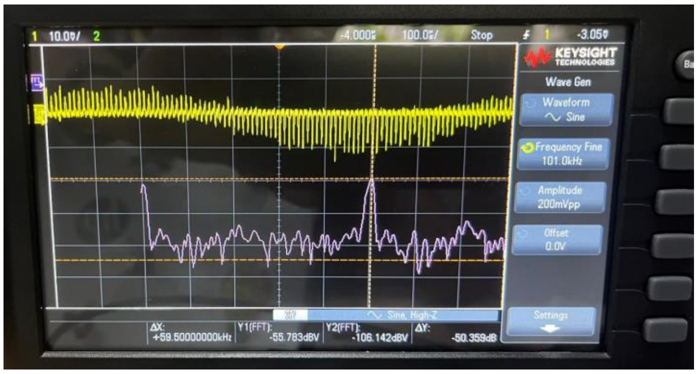

Fig. 18. FFT of Output (V_{IF}) of (Implemented) Switch for V_{OSC}=101kHz

5) 102kHz

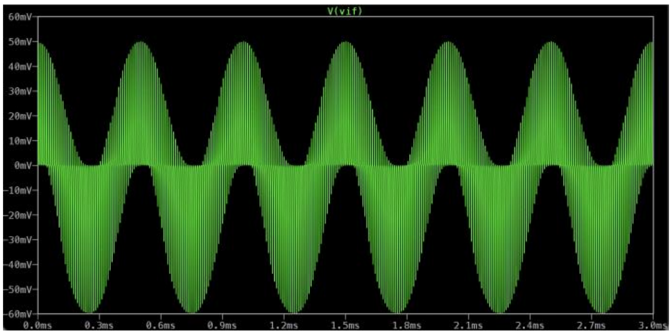

Fig. 19. Output (V_{IF}) of Switch for Vin = 102 kHz

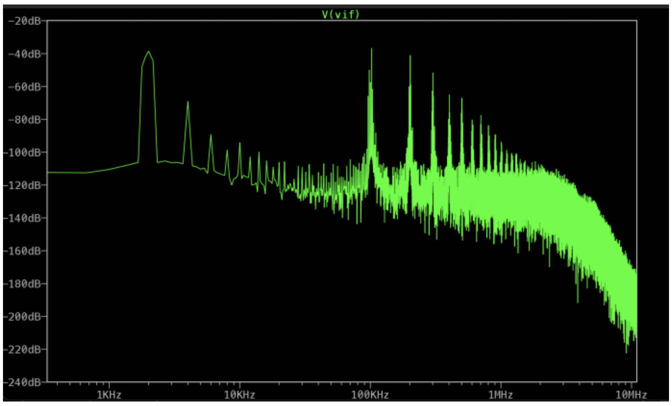

Fig. 20. FFT of Output (V_{IF}) of Switch for V_{OSC} = 102 kH

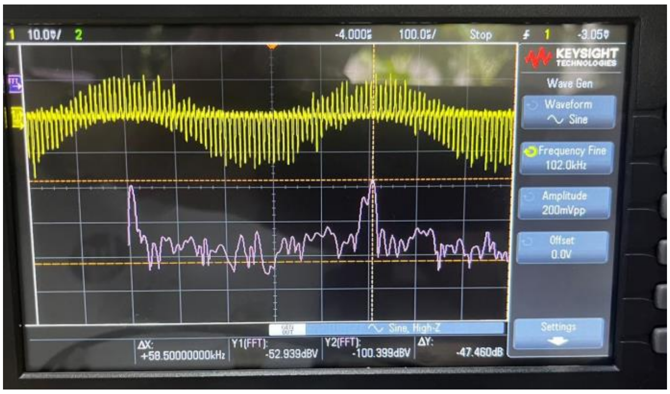

Fig. 21. FFT of Output (V_{IF}) of (Implemented) Switch for V_{OSC}=102 kHz

6) 105kHz

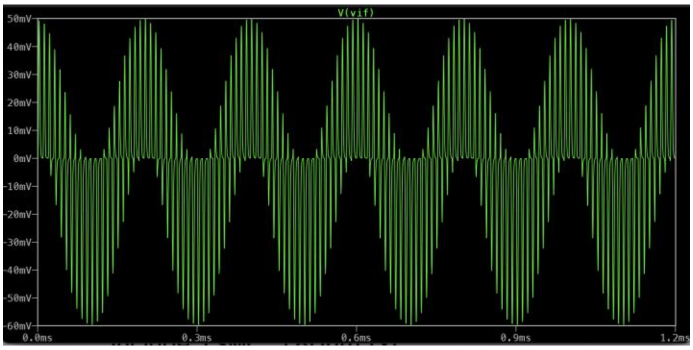

Fig. 22. Output (V_{IF}) of Switch for Vin = 105 kHz

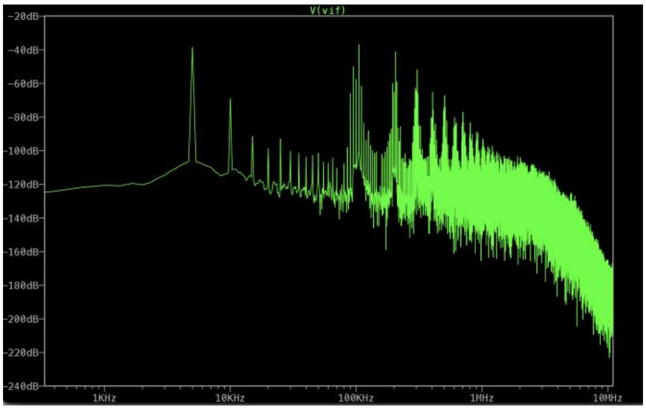

Fig. 23. FFT of Output (V_{IF}) of Switch for V_{OSC} = 105 kH

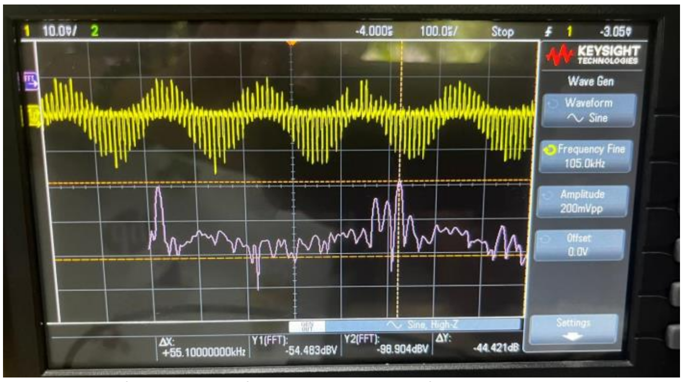

Fig. 24. FFT of Output (V_{IF}) of (Implemented) Switch for V_{OSC} = 105 kHz

III. QUADRATURE OSCILLATOR

Quadrature Oscillator integral part of the down converter.

An oscillator is an electronic circuit that generates a periodic, repetitive waveform without the need for an external input signal. At its core, an oscillator operates based on positive feedback. Positive feedback occurs when a portion of the output signal is fed back to the input with a phase shift of 180 degrees or more. This feedback reinforces the input signal, causing it to sustain and oscillate.
To generate sine and cosine waveforms from a DC input signal, an oscillator is used in conjunction with phase-shifting networks or quadrature generation techniques. These networks introduce a phase shift between the original waveform and the derived waveforms, resulting in two output signals that are 90 degrees out of phase with each other.

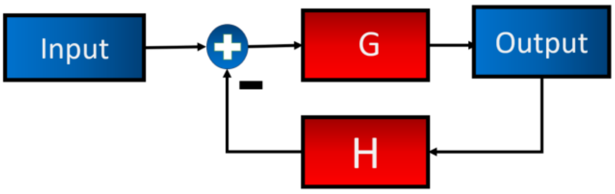

Fig. 25. Generic Block Diagram for Oscillator

For any oscillator to work, it must follow the Barkhausen conditions:

1) $|GH| \geq 1$
2) $\angle GH = 180^o$

Here, we can see that:

$$\frac{V_{OUT}}{V_{IN}} = \frac{G}{1+GH}$$

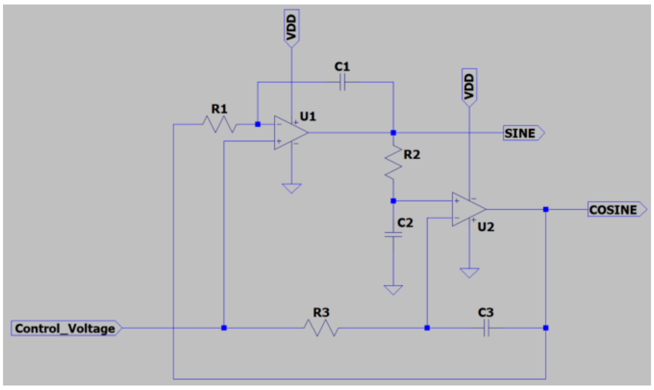

Fig. 26. Generic Block Diagram for Oscillator

Here,

$$GH(s) = \left(\frac{1}{sR_1C_1}\right)\left(\frac{1+sR_3C_3}{sR_3C_3(1+sR_2C_2)}\right)$$

When $R_1C_1 = R_2C_2 = R_3C_3 = RC$,

$$GH(s) = \frac{1}{(sRC)^2} \implies GH\left(\frac{j}{RC}\right) = -1 = 1\angle 180^o$$

We will try to design an oscillator that generates sinusoids of frequency 100kHz.

$$\frac{1}{2\pi RC} = 100KHz \implies RC = \frac{1}{2\pi 10^5}s = 1.59\mu s$$

v2 = A(v5 − v1), v4 = A(0 − v3)
R1C1 = R2C2 = R3C3
(v1 − v2)SC1 + v1 R1 = 0
(v2 − v1)SC1 + v2 − v3 R2 = 0
(v3 − v4)SC2 + v3 − v2 R2 = 0
(v4 − v3)SC2 + v4 − v5 R3 = 0
v5 − v4 R3 + (v5)SC3 = 0
and the equation for loop gain was found out to be - Aβ = 1 (SRC)2
(10) f = 1 2πRC , f = 100kHz

However, such a value of RC does not give correct results in the simulations. On trial with R = 1591Ω and C = 1nF, we observe a frequency of 70.115kHz. To account for this we decided to lower the RC product to 0.5μs (the decision was based on some experimentation over R and C values). The values picked were:

R = 500Ω, C = 1nF

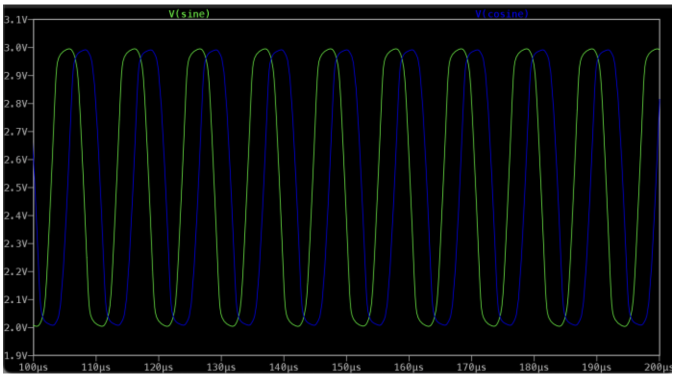

Fig. 27. Oscillator Simulation

Parameters Observed:

- Amplitude: 984.06873mVpp
- Frequency: 97kHz
- Phase Difference:

2π(97kHz)(2.5384615μs) = 1.547rad = 88.347º

The exact values did not work in real life. The frequency observed was lower than what we wanted. Hence, it was required to lower the RC value. So, the following parameters were used:

- R=390Ω
- C=1nF
- V_{DD}=7.33V
- Control Voltage = 2.3V

Following are the results observed:

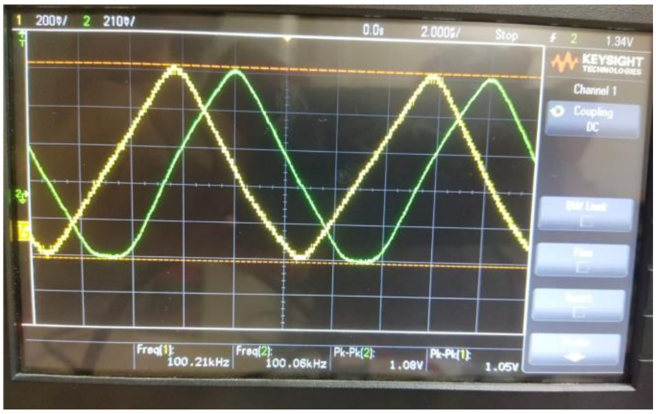

Fig. 28. Oscillator Results

Parameters Observed for Wave 1:

- Amplitude: 1.08Vpp
- Frequency: 100.06kHz

Parameters Observed for Wave 2:

- Amplitude: 1.05Vpp
- Frequency: 100.21kHz

Phase Difference ≈ $(360^o)(10^5)(2.4 \times 10^{-6}) = 86.4^o$

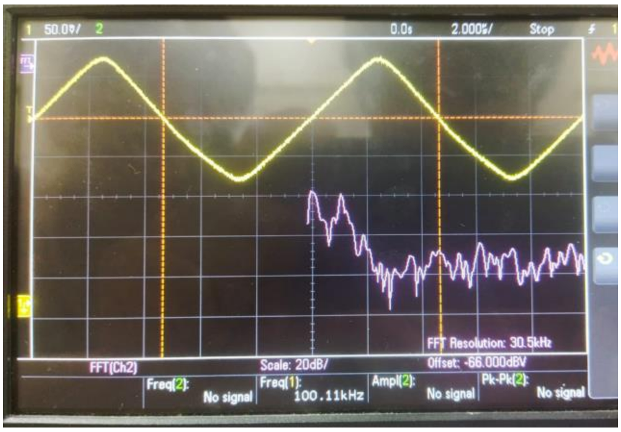

Fig. 29. FFT of Wave

1

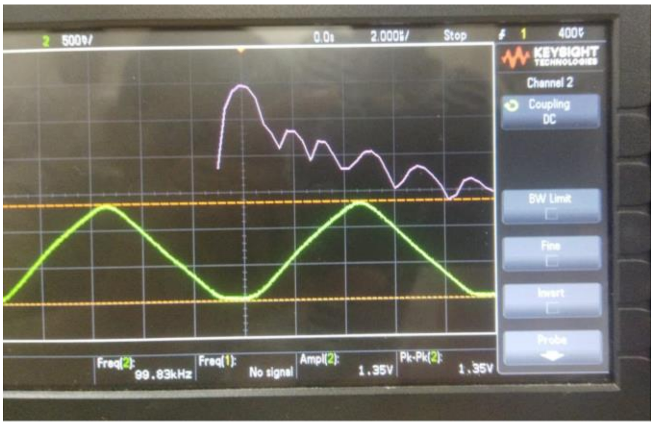

Fig. 30. FFT of Wave 2

IV. LOW PASS

A low pass filter (LPF) is an essential electronic component that allows signals with a frequency lower than a specific threshold, known as the cutoff frequency, to pass through it while attenuating (reducing) components of the signal that are higher than this frequency. The purpose of a low pass filter is to eliminate unwanted high-frequency noise and to smooth the output of signals.

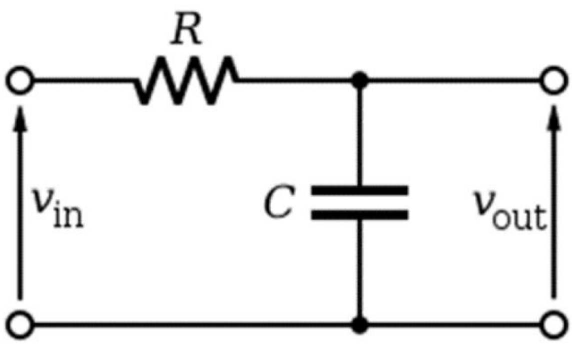

Fig. 31. Reference RC Circuit

BASIC IMPLEMENTATION OF A RC CIRCUIT:

Resistor (R): This component restricts the flow of electric current, creating a voltage drop across its terminals according to Ohm's Law.

Capacitor (C): Capacitors store and release electrical energy, and their ability to pass alternating current (AC) depends on the frequency of the AC signal. The impedance of a capacitor decreases as the frequency increases, making it more conductive at higher frequencies.

BASIC WORKING OF A RC CIRCUIT:

When a signal enters an RC low pass filter, both the resistor and the capacitor influence its behaviour:
Voltage Divider: The resistor and capacitor form a voltage divider circuit. The output voltage of the filter is measured across the capacitor.
Frequency Response: At low frequencies, the capacitor's impedance is high relative to the resistor, so most of the input voltage appears across the capacitor, and thus, the signal passes through unchanged. At high frequencies, the capacitor's impedance is lower, allowing more of the signal to drop across the resistor and less across the capacitor, effectively attenuating the signal.

EXPLANATION OF THE OUTPUT:

The reactance of the capacitor in the above picture is given by:
$XC = 1/j\omega C$.
From this formula, we can see that the reactance is inversely proportional to the angular frequency. This means that as the frequency of the input signal increases, the reactance decreases.
At Low Frequencies: When ω (angular frequency) is small, ωCR is also insignificant compared to 1. Therefore, $1+\omega CR\ 1 \approx 1$, and $Vout \approx Vin$. This indicates that low-frequency signals pass through the filter with little attenuation.
At High Frequencies: As ω increases, ωCR becomes much larger than 1.
The term $1+\omega CR$ becomes much smaller, approaching zero. Thus, Vout is significantly reduced compared to Vin, leading to the attenuation of high-frequency signals.
The nature of the capacitor's reactance explains why a low pass filter attenuates high-frequency signals:
Low ω (Frequency): High reactance means fewer current flows through the capacitor, and more voltage is dropped across it, allowing the signal to pass with less attenuation. High ω (Frequency): Low reactance allows more current to flow through the capacitor, resulting in a greater voltage drop across the resistor and less across the capacitor, which means the high-frequency signal components are significantly reduced.

MATHEMATICAL DERIVATION OF A LOW PASS FILTER:

The cutoff frequency of the low pass filter can be calculated as follows:
Using KVL: $VOUT = XC \cdot (Vin/XC+XR)$, where XC and XR are the impedances of the capacitor and resistor, respectively.
$Vout/Vin = XC/XC+XR$ (1)
To obtain the -3dB frequency of the given response, we proceed as follows. $-3 = 20\log|(Vout/Vin)|$ (2)
From equation (1),
$|Vout/Vin| = \sqrt{(1/1+(\omega RC)2)}$ (3)
Solving equations (2) and (3),
we get $\omega = 1/RC$ $fC = 1/2\pi RC$, where fC is the cutoff frequency of the filter.

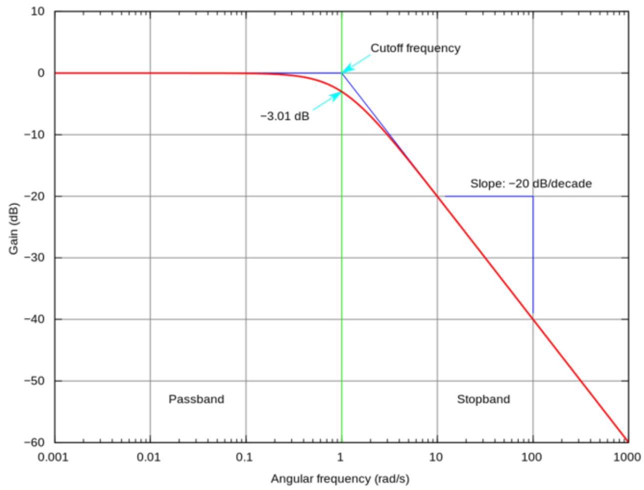

Fig. 32. Frequency Response of an RC Circuit

Given that the –3dB cutoff of the low pass filter should be 2kHz. Thus, fC should be equal to 2kHz.
2*10^3 = 1/2πRC. Using this equation, we choose the values of R and C such that fC becomes close to 2.8kHz as if the –3dB cutoff frequency comes out to be 2kHz then there will be attenuation at 2kHz also which we don't want, we want input of 2kHz to pass through the filter without any attenuation thus taking a value of –3dB cutoff greater than 2kHz.
Taking R and C values of the low pass filter as follows: R = 1.26kohm C = 47nF

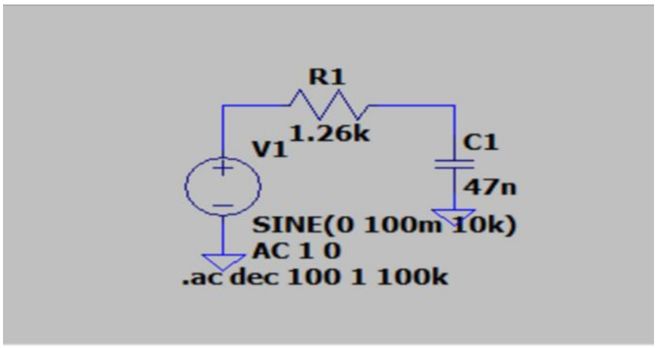

Fig 33. LTSpice Circuit

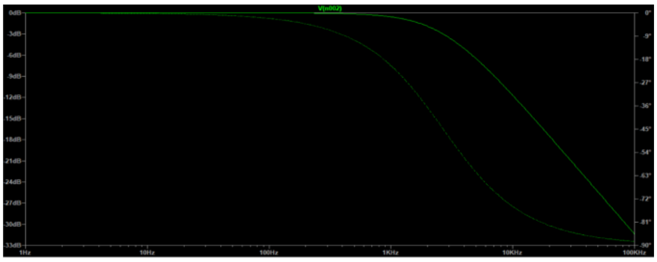

Fig 34. LTSpice Frequency Response

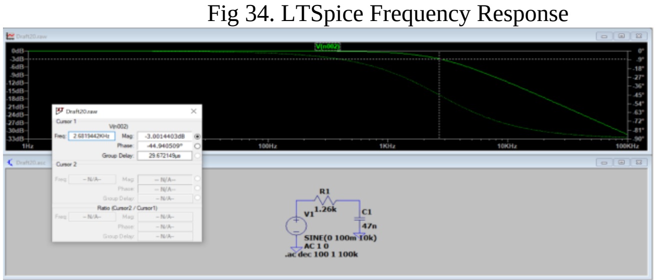

Fig 35. LTSpice –3dB frequency

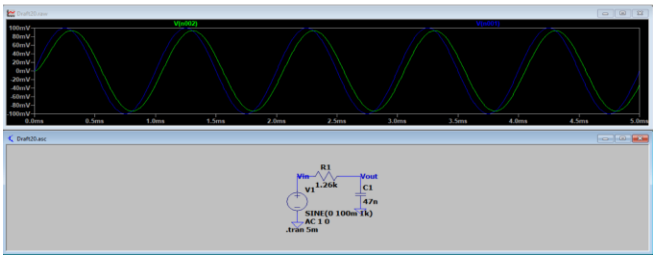

Fig 36. Output for 1kHz

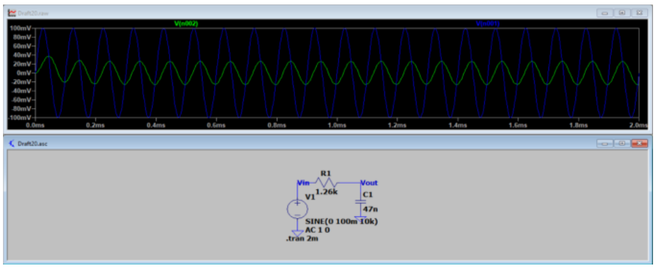

Fig 37. Output for 10kHz

OBSERVATIONS:

Low pass filters (LPFs) are designed to allow signals with frequencies below a predetermined threshold, known as the cutoff frequency, to pass through with minimal or no attenuation, while attenuating signals with frequencies above this threshold.
From the above plots, we can see that the input signals which have frequency lower than that of the cutoff are minimally attenuated(1kHz) i.e. the output and the input signals are almost equal, while the input signals with frequency more than the cutoff are highly attenuated(10kHz) i.e. the most of the output signal is attenuated because the low pass filter does not allow frequencies above 2kHz to pass through it.

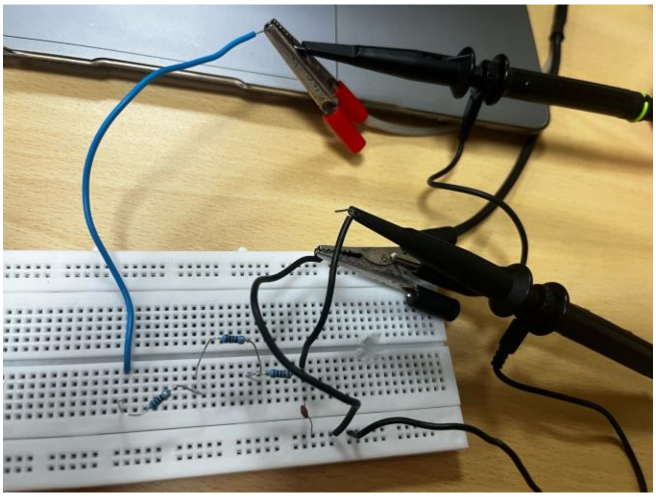

Fig 38 CIRCUIT

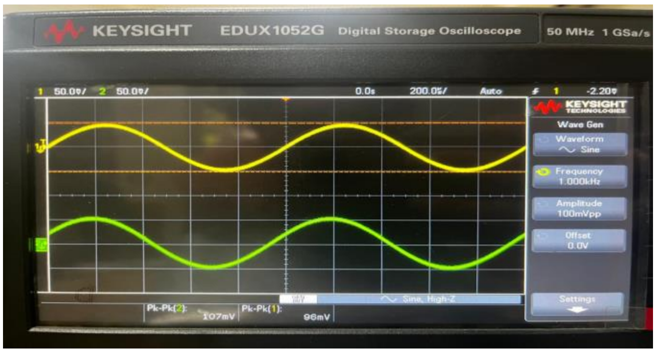

Fig 39. Output for 1kHz

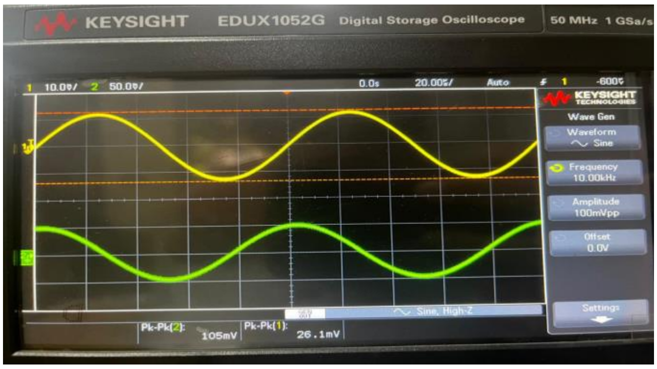

Fig 40. Output for 10kHz

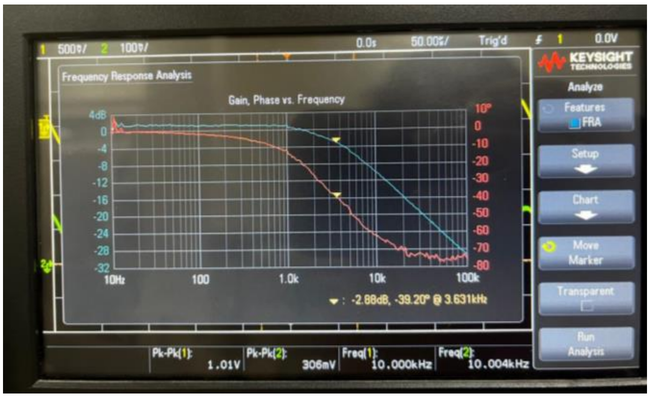

Fig 41. Frequency Response

V. FINAL RESULT

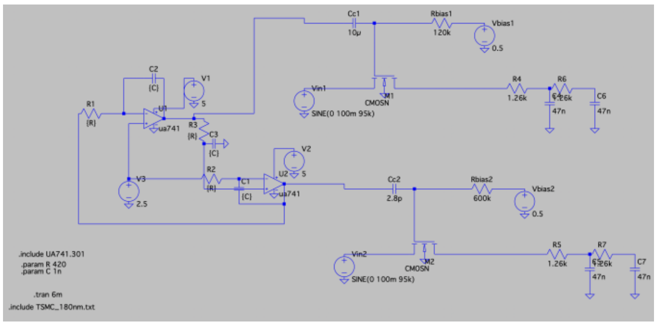

Fig. 42. Final Design

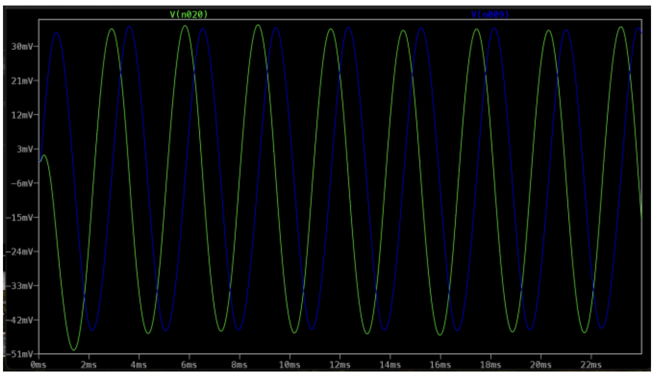

Fig. 43. Spice Results

AFTER PASSING THE OUTPUT OF OSCILLATOR THROUGH MIXER:

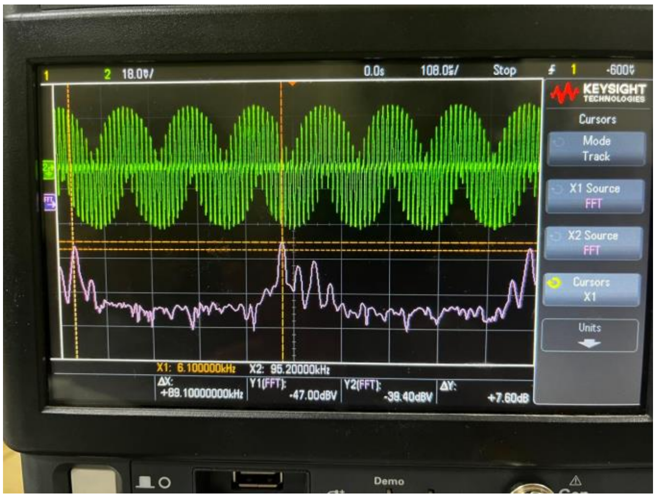

Fig 44. Output of sine after passing through mixer

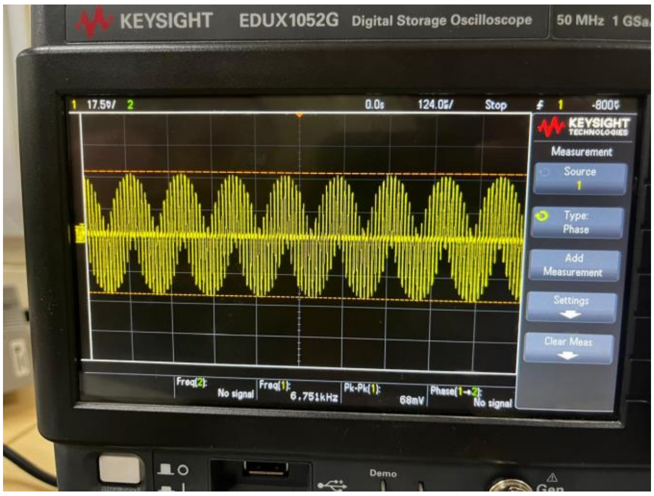

Fig 45. Output of cosine after passing through mixer

FINAL RESULT AFTER PASSING THROUGH LOW PASS FILTERS:

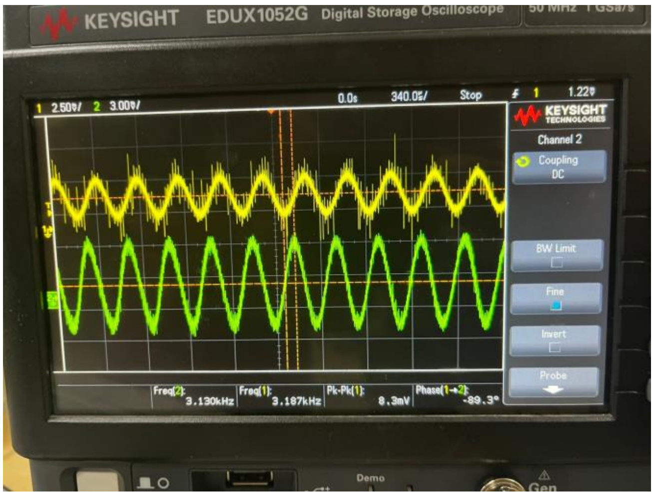

Fig 46. Total output after lowpass filter

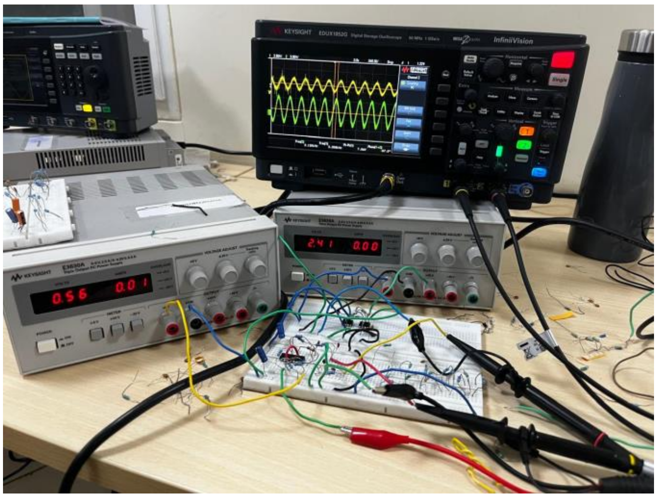

Fig 47. Total circuit figure

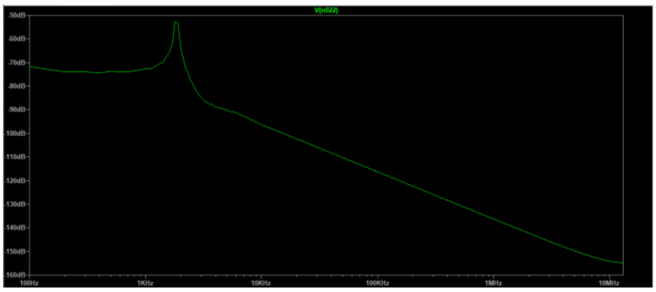

Fig. 48. FFT of output after low pass

Peak at 1.9Khz

PARAMETERS	SIMULATED	MEASURED
Oscillator frequency	98.2kHz	100.2kHz
Oscillator Amplitude (I-phase)	1VPP	1.08VPP
Oscillator Amplitude (Q-phase)	1V	1.05VPP
Input frequency	97kHz	97kHz
IF	5.003kHz	6.75kHz
Supply	5V	7.3V
VBIAS	0.5V	0.5V
CC	10u	10u

OBSERVATION OF THE FINAL OUTPUT:

The values of frequencies are around 3kHz as the cutoff frequency for our low pass filter is around 2.8kHz and due to some different resistor values as exact ones were not available the frequency comes out to be a little higher.

CONCLUSION:

Designing a quadrature down oscillator involves a careful balance of selecting appropriate components and implementing techniques to achieve the desired performance characteristics.

I) Choosing active and passive components suitable for the oscillator circuit, considering factors such as frequency response, distortion characteristics, and stability.
II) Designing the oscillator circuit using fundamental active and passive components, ensuring proper biasing, stability, and frequency response.
III) Addressing issues related to slew rate limitations, which can cause waveform distortion, by selecting components with adequate slew rates or employing compensation techniques.
IV) Fine-tuning the oscillator to ensure the output signals have frequencies within the desired range, and the phase relationship meets the quadrature requirement.
V) Minimizing harmonic distortion and waveform distortion by optimizing component values, employing filtering techniques, and ensuring proper signal conditioning.

REFERENCES:

[1] Ron Mancini, Texas Instruments “Design of op amp sine wave oscillators”.

[2] Bruce Carter and Thomas R. Brown, Texas Instruments “Handbook of Operational Amplifier Applications”

[3] Farsheed Mahmoudi, “Quadrature Down-converter for Wireless Communications”

[4] Sedra Smith, “Microelectronic Circuits”