Quadrature Down Oscillator

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***Abstract*—In modern-day communication systems, information is sent in the form of signals of very high frequency. At the receiver, this signal is converted into signals of lower frequencies. One of the converters used for this process is the Quadrature Down Converter (QDC), which is used widely in mobile communication. In this project, we would implement a rudimentary quadrature down converter.**

***Index Terms*—Quadrature Down Converter (QDC), Mobile Communication**

I. Introduction

In communication systems, down converters are used often to convert the radio frequency signals to the required intermediate frequency signals. During this process, it is necessary to have the levels of induced noise due to the conversion, as low as possible. A QDC converts a high-frequency input signal into two low-frequency signals with a phase difference of 90^o.

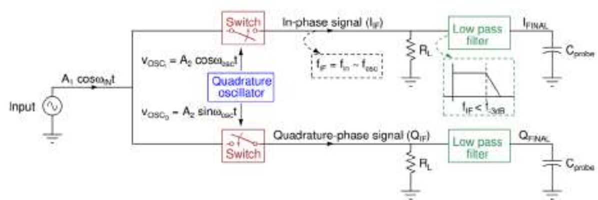

Fig. 1. Reference circuit diagram for QDC

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.
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.

II. Switch (Mixer)

The voltage-controlled switches are realized using MOSFETs. When the gate is biased close to the threshold voltage of the MOSFET, during the positive have of the gate signal (which is generated using the quadrature oscillator), the MOSFET is in linear mode, and during the negative cycle the MOSFET is in cut off mode. The output of the switch is equivalent to multiplying the input signal at source of MOSFET to a square wave. 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.

$\therefore$ The multiplied signals are of the form cosAcosB and sinAcosB.

$\because$ 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)

$\therefore$ The output of the switch can be expressed as follows :

$sinB \cdot f(x)$.... (1) ,where

$f(x) = 1, 0 \leq t \leq \omega/2$

$f(x) = 0, \omega/2 < t \leq \omega$

f(x) can be represented by its fourier series and the above equation can be written as :

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

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 modulation 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 C_c is to AC couple the signal generated by the oscillator. The resistor (R_{BIAS}) ensures that the gate of the MOSFET is not directly connected to AC ground in the small signal model.

A high R_{BIAS} is necessary to avoid the flow of a very high small signal current through the bias resistor. Now, in the small signal model, C_C and R_{BIAS} form a high pass filter. So, the value of C_C should be high enough to allow a signal of 100kHz to pass conveniently.

$\therefore$ The values we have chosen for our circuit are:

$C_c = 10\mu F$

$R_{BIAS} = 10k\Omega$

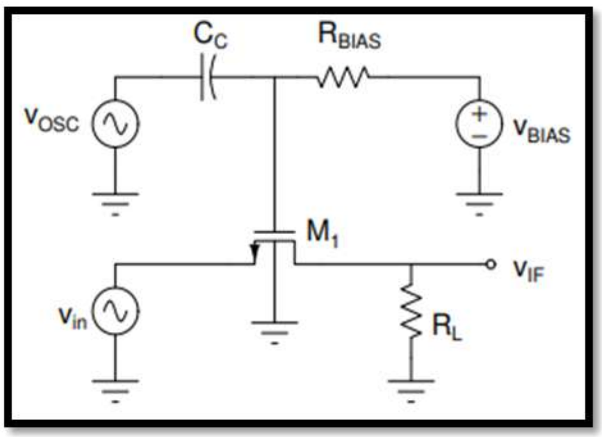

Fig. 2. Reference circuit diagram for Switch

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, $\implies$ 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.

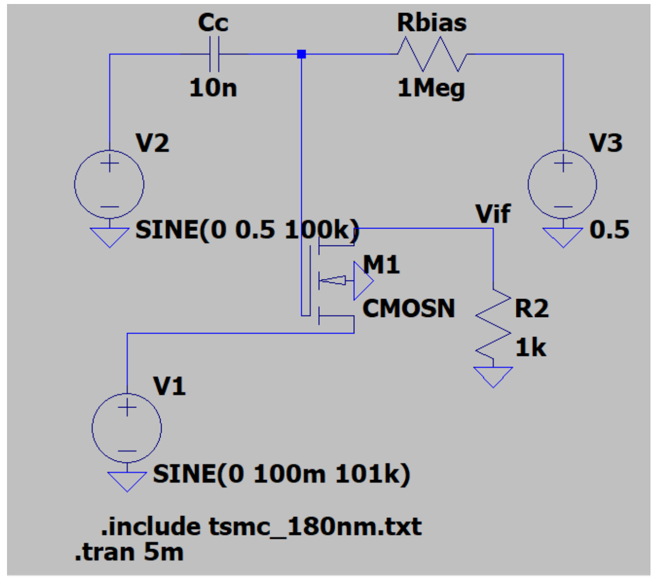

Fig. 3. LTSpice simulated circuit for switch (mixer)

The following is the output observed for the switch:

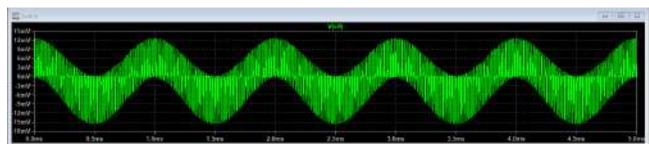

Fig. 4. Output (V_{IF}) of Switch

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 :

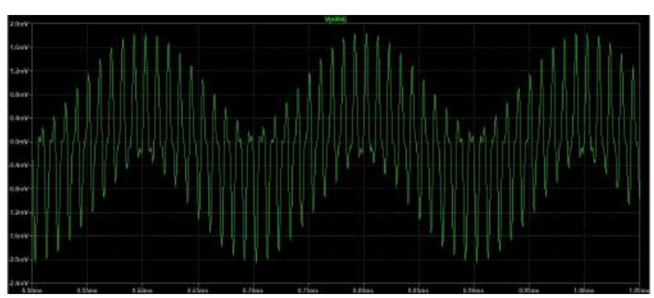

Fig. 5. Output (V_{IF}) of Switch for V_{OSC} = 95 kHz

The corresponding FFT plot :

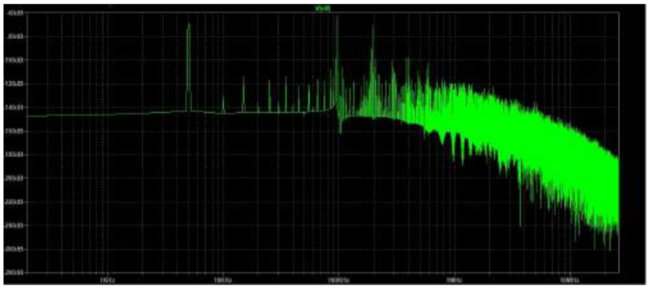

Fig. 6. FFT of Output (V_{IF}) of Switch for V_{OSC} = 95 kHz

2) 98kHz :

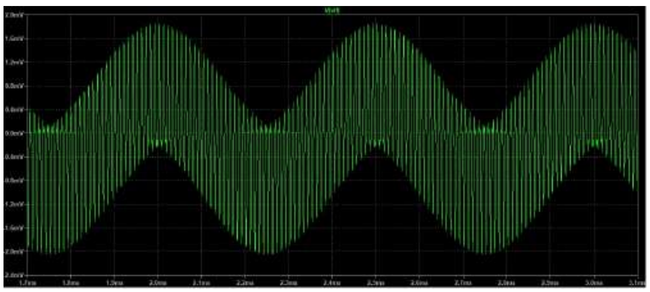

Fig. 7. Output (V_{IF}) of Switch for V_{OSC} = 98 kHz

The corresponding FFT plot :

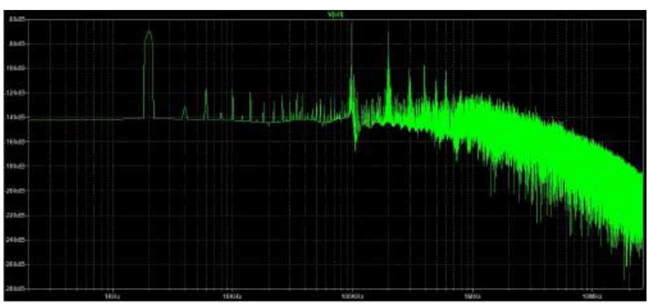

Fig. 8. FFT of Output (V_{IF}) of Switch for V_{OSC} = 98 kHz

3) 99kHz :

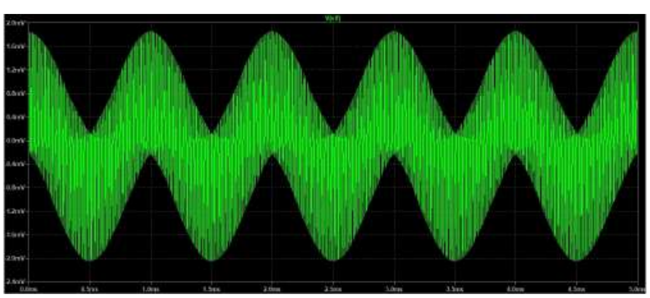

Fig. 9. Output (V_{IF}) of Switch for V_{OSC} = 99 kHz

The corresponding FFT plot :

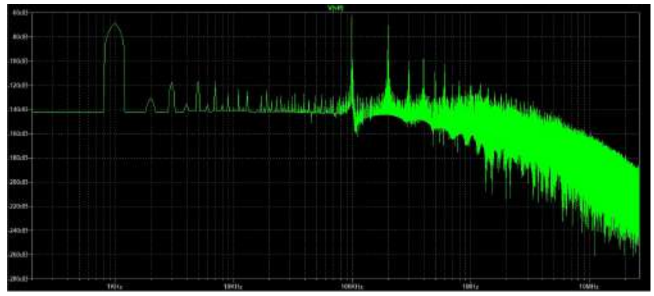

Fig. 10. FFT of Output (V_{IF}) of Switch for V_{OSC} = 99 kHz

4) 101kHz :

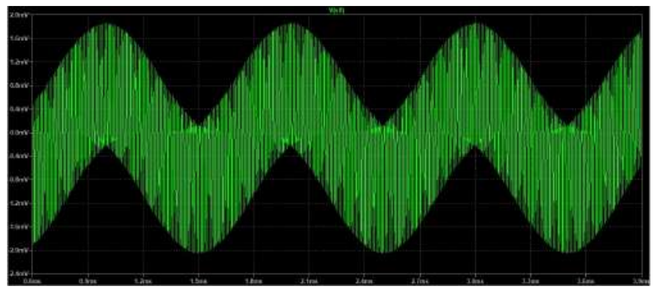

Fig. 11. Output (V_{IF}) of Switch for V_{OSC} = 101 kHz

The corresponding FFT plot :

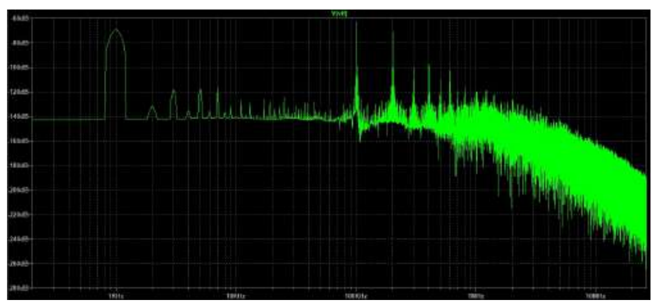

Fig. 12. FFT of Output (V_{IF}) of Switch for V_{OSC} = 101 kHz

5) 102kHz :

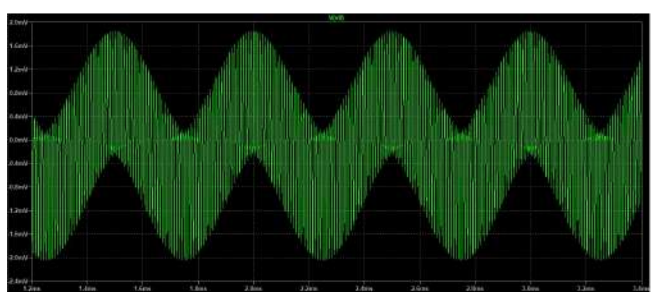

Fig. 13. Output (V_{IF}) of Switch for V_{OSC} = 102 kHz

The corresponding FFT plot :

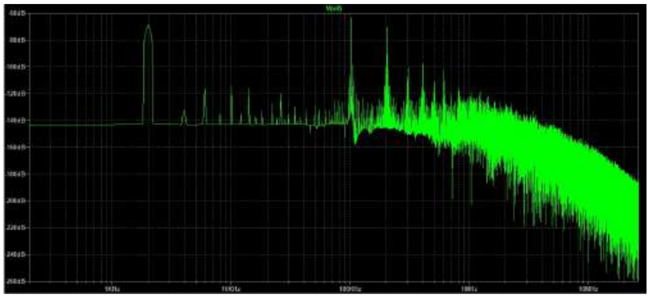

Fig. 14. FFT of Output (V_{IF}) of Switch for V_{OSC} = 102 kHz

6) 105kHz :

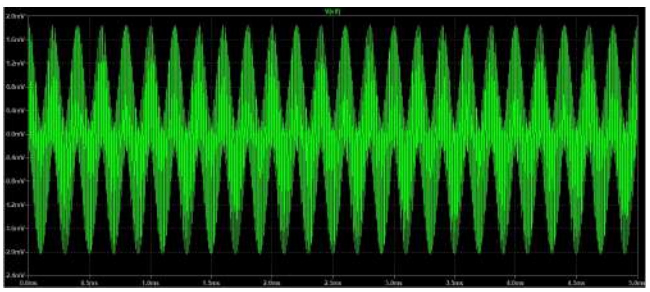

Fig. 15. Output (V_{IF}) of Switch for V_{OSC} = 105 kHz

The corresponding FFT plot :

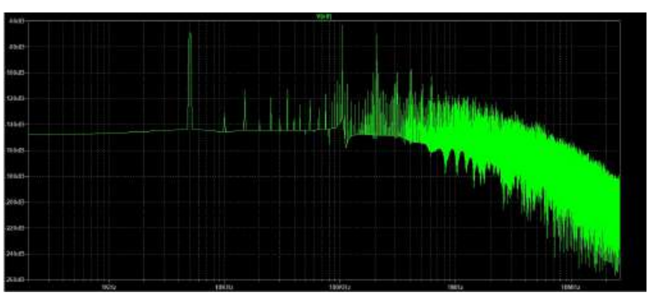

Fig. 16. FFT of Output (V_{IF}) of Switch for V_{OSC} = 105 kHz

Testing the output on oscilloscope :

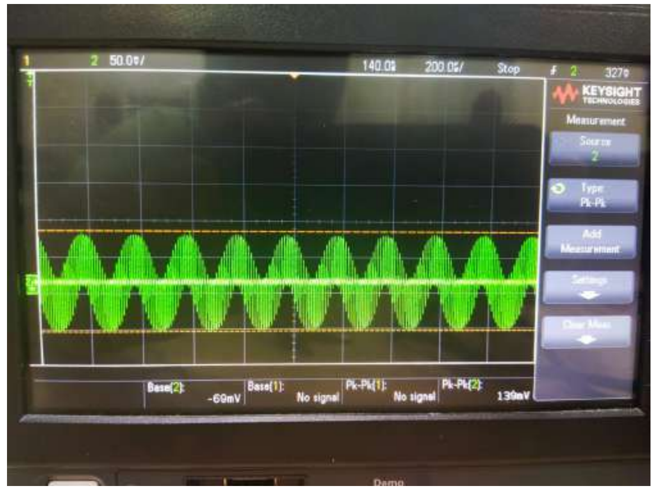

Fig. 17. Oscilloscope response for the switch 1

FFT plot for the corresponding oscilloscope response:

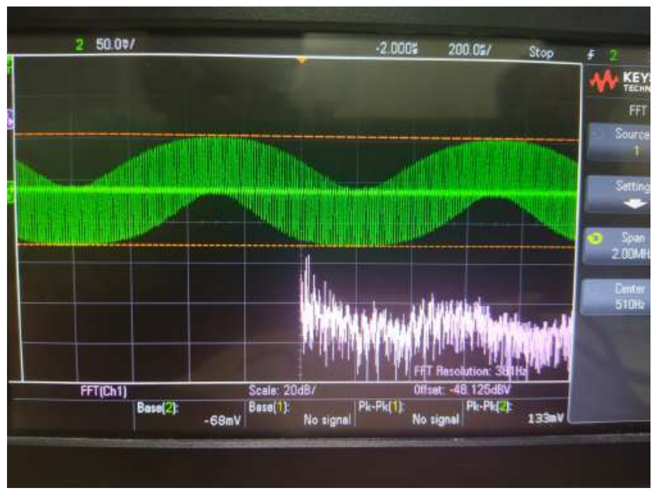

Fig. 18. FFT of Oscilloscope response for the switch 1

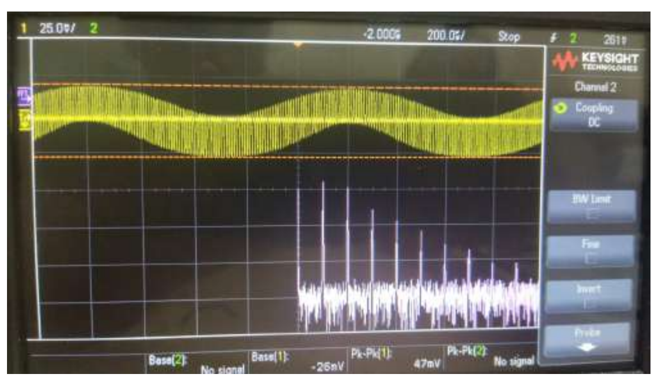

Fig. 19. Combined image for oscilloscope response and FFT of oscilloscope response for switch 2

$\because$ We require 2 mixers for our given circuit, the above plots are distinct for the 2 mixers.

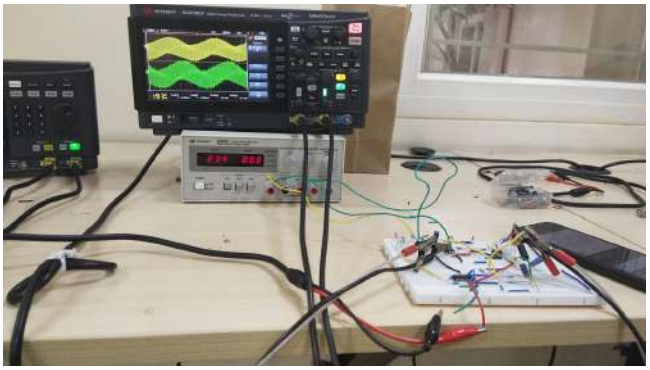

Fig. 20. Measurement Setup

As can be seen, as soon as the switch enters the cutoff region, due to high frequency of the oscillator, the output starts to rise again.

III. Quadrature Oscillator

This is an integral part of the down converter and probably the part we struggled with the most.

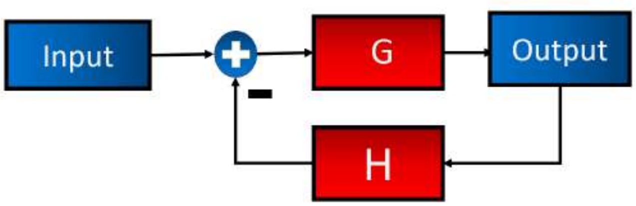

Fig. 21. Generic Block Diagram for Oscillator

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:

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

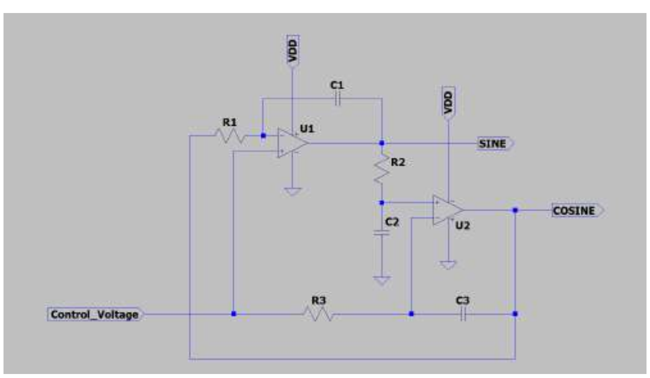

Fig. 22. Generic Block Diagram for Oscillator

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.

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

However, such a value of RC does not give correct results in the simulations. On trial with $R = 1591\Omega$ and $C = 1nF$, we observe a frequency of $70.115kHz$. To account for this we decided to lower the RC product to $0.4\mu s$ (the decision was based on some experimentation over R and C values). The values picked were:

$$R = 400\Omega, C = 1nF$$

The following was the plot observed:

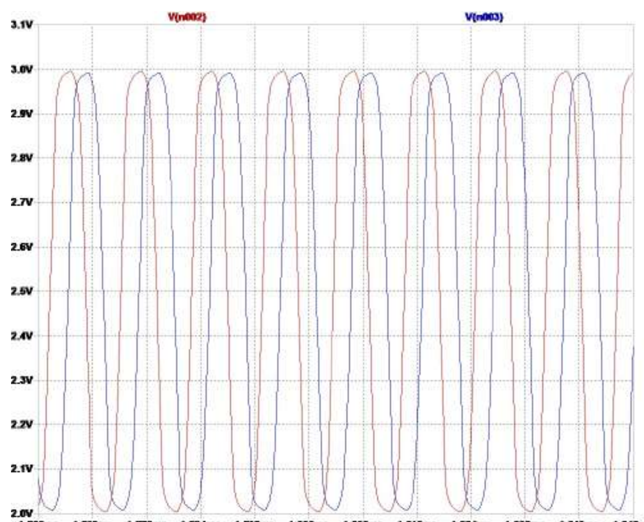

Fig. 23. Oscillator Simulation

Parameters Observed:

- Amplitude: 984.06873mVpp
- Frequency: 97kHz
- Phase Difference: $2\pi(97kHz)(2.5384615\mu s) = 1.547\text{rad} = 88.347^o$

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:

- $R = 100\Omega$
- $C = 1nF$
- $V_{DD} = 8V$
- Control Voltage = $2.3V$

This fixes the frequency issue but the amplitude is a little larger than $1V_{pp}$, but that can be easily fixed using voltage dividers. Following are the results observed:

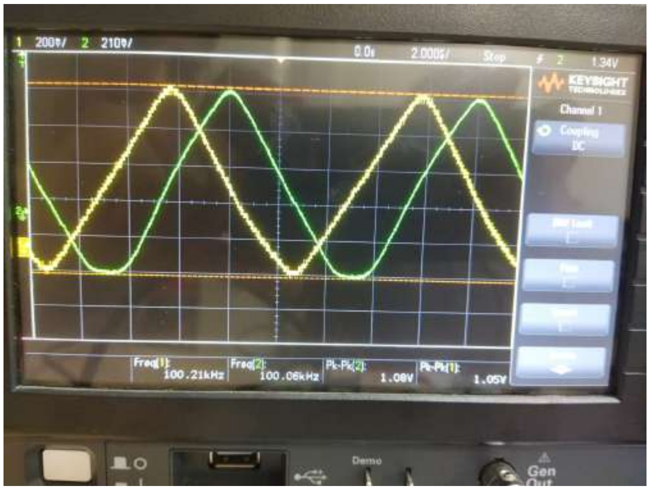

Fig. 24. Oscillator Results

Parameters Observed for Wave 1:

- Amplitude: 1.08Vpp
- Frequency: 100.06kHz

Parameters Observed for Wave 2:

- Amplitude: 1.05Vpp
- Frequency: 100.21kHz

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

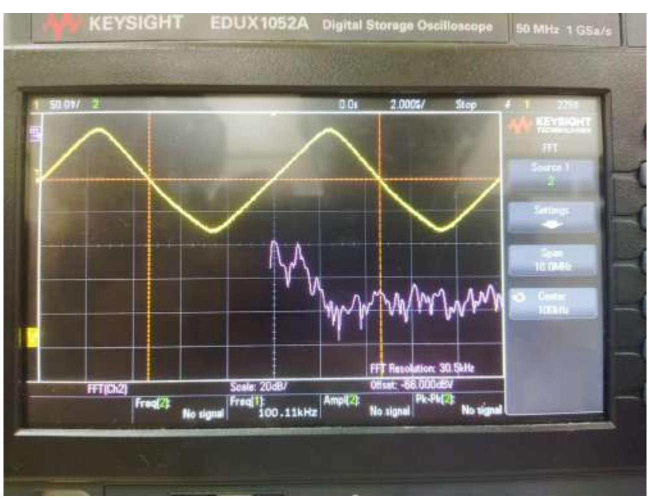

Fig. 25. FFT of Wave 1

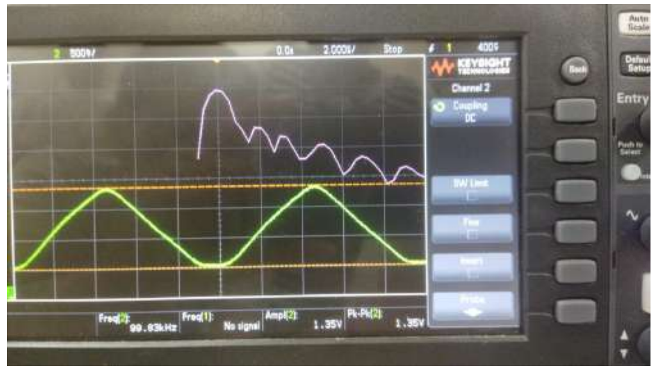

Fig. 26. FFT of Wave 2

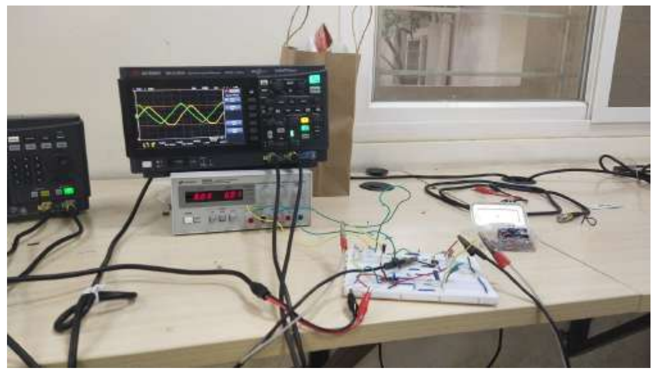

Fig. 27. Measurement Setup

IV. Low Pass Filter

The main objective of the low pass filter is to filter out the high frequency signals which were generated by the switch (mixer). The main principle on which an ideal low pass filter works is that, only the signals with frequencies $\leq$ the cutoff frequency pass through it. However, in real life, there is some attenuation of the signal, i.e. the amplitude of the signal is decreased slightly when it is passed through a low pass filter.

The circuit used for the implementation of the low pass filter is as follows:

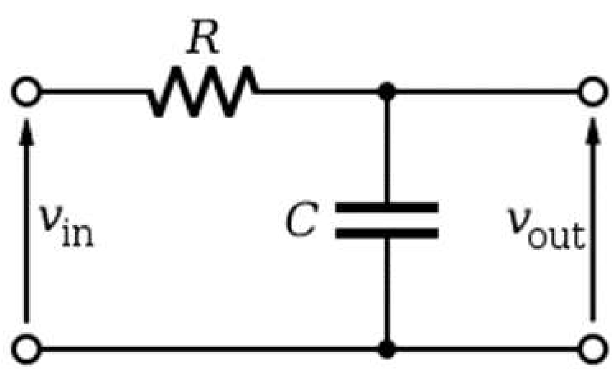

Fig. 28. Reference circuit diagram for the low pass filter

The working of the low pass filter can be explained as follows:

The reactance of the capacitor in the above picture is given by: $X_C = \frac{1}{j\omega C}$

From the above equation it is clear that the reactance offered by the capacitor is inversely proportional to the angular frequency of the input signal. $\because$ V_{OUT} is directly proportional to the reactance of the capacitor, at higher values of angular frequencies, V_{OUT} is low and similarly at lower values of angular frequencies, V_{OUT} is high $\implies$ attenuating effect is observed as the high frequency signal get attenuated, allowing only the low frequency signals to pass.

The cutoff frequency of the low pass filter can be calculated as follows:

Using KVL:

$V_{OUT} = X_C \cdot (\frac{V_{IN}}{X_C + X_R})$, where $X_C and X_R$ are the impedances of the capacitor and resistor respectively.

$\implies \frac{V_{OUT}}{V_{IN}} = \frac{X_C}{X_C + X_R}$ ...(1)

To obtain the -3dB frequency of the given response, we proceed as follows.

$-3 = 20log|(\frac{V_{OUT}}{V_{IN}})|$....(2)

From equation (1),

$|\frac{V_{OUT}}{V_{IN}}| = \frac{1}{\sqrt{1+(\omega RC)^2}}$....(3)

$\implies$ Solving equations (2) and (3), we get

$\omega = \frac{1}{RC}$

$\implies f_C = \frac{1}{2\pi RC}$, where f_C is the cutoff frequency of the filter.

The amplitude v/s frequency plot of the above equation can be observed as follows:

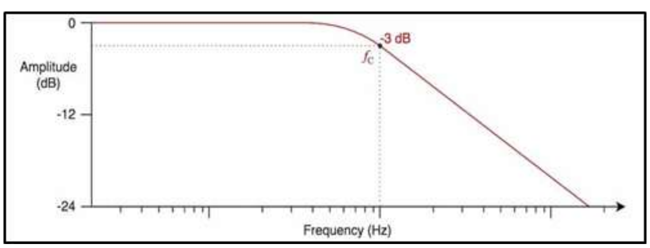

Fig. 29. Amplitude v/s Frequency response plot

Since the desired value of output is below 2 kHZ, the cutoff frequency would be 2 kHz.

$\implies 2 \cdot 10^3 = \frac{1}{2\pi RC}$

We have chosen values of R and C such that the cutoff frequency is close to 2 kHz,

R = 80Ω

C = 1μF

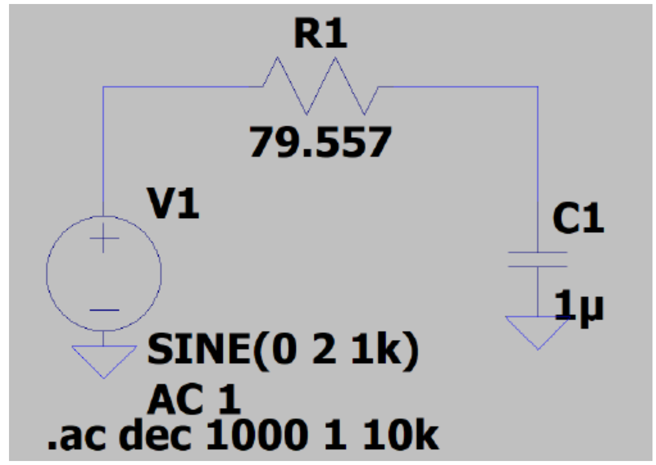

Fig. 30. LTSpice circuit of Low Pass Filter

The corresponding frequency response analysis for the above circuit is as follows:

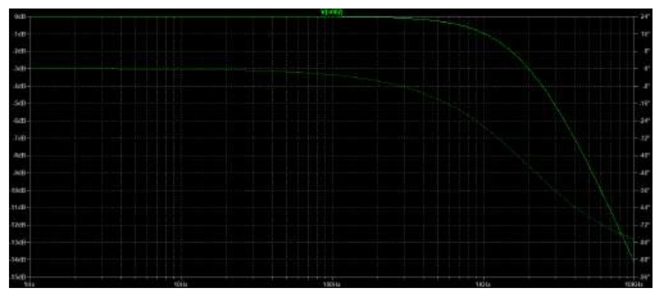

Fig. 31. Frequency response plot of LPF

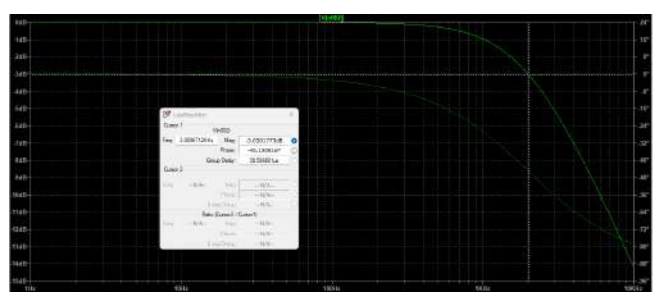

Fig. 32. Measuring the -3dB frequency on frequency response plot of LPF

The plots below show the response of the LPF to different frequency signals :

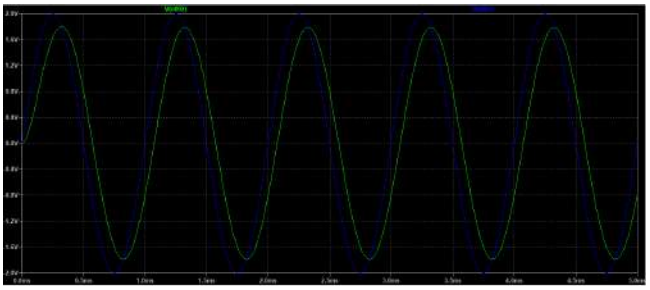

Fig. 33. Response of LPF to a signal of frequency 1 kHz

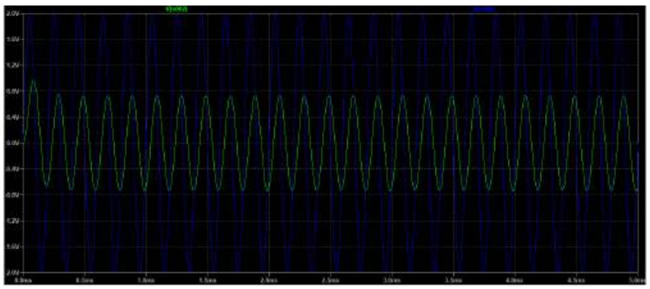

Fig. 34. Response of LPF to a signal of frequency 5 kHz

From the above plots, it is clear that the low pass filter allows the signals with frequency less than the cutoff frequency to pass, without any attenuation. Signals with frequency higher than the cutoff frequency are attenuated (5 kHz frequency signal is attenuated).

Below is the Frequeny Response Analysis of the Low pass filter on oscilloscope:

Fig. 35. Frequency Response Analysis of the Low pass filter

The irregular rise in the end of the FRA plot can be explained by the inductance of the channel and other components of the oscilloscope which causes some LC oscillations resulting to resonance, causing the irregular behaviour.

The observed -3 dB frequency is around 2 kHz, thus verifying our calculations.

Following are the observed plots on the oscilloscope:

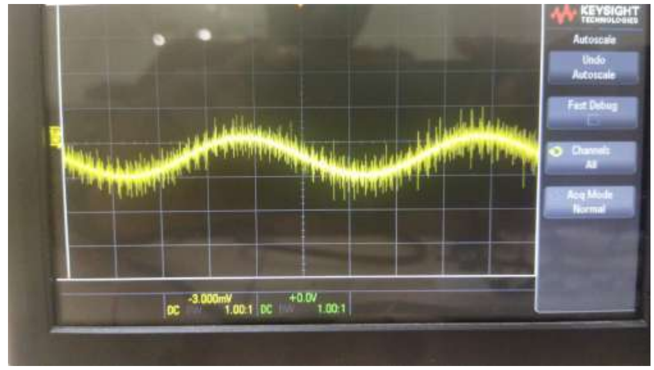

Fig. 36. Passing the switch output through the Low Pass Filter

When the output of the switch(mixer) is passed through the low pass filter, the frequency of the observed signal is $\leq$ cutoff frequency of the LPF. This output depends on the different frequency components generated by the oscilloscope and that of the input signal. For our given signal, the output wave has a frequency approximately equal to 1 kHz, which is less than the cutoff frequency.

V. Final Results

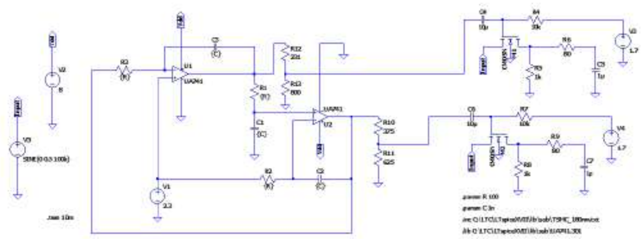

Fig. 37. Final Design

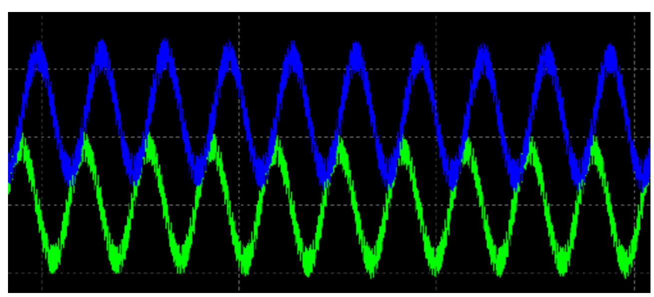

Fig. 38. Spice Results

Observations from the spice results:

- Amplitude: 2.1534594mVpp
- Frequency: 3.1298982KHz
- Phase Difference: $(360^o)(3.13kHz)(81.4\mu s) = 91.721^o$

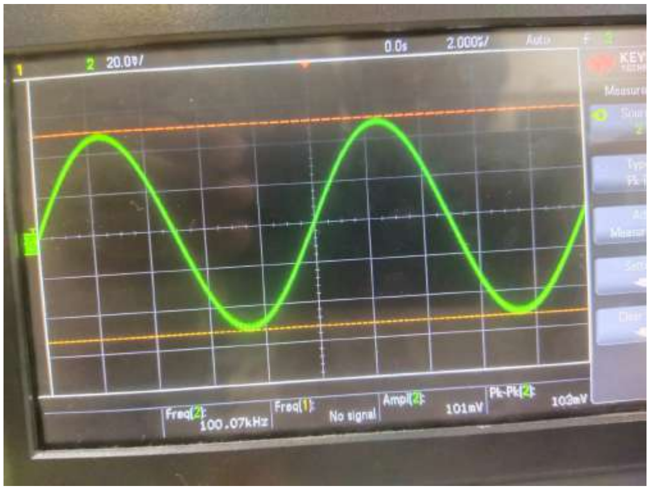

Fig. 39. Input Signal

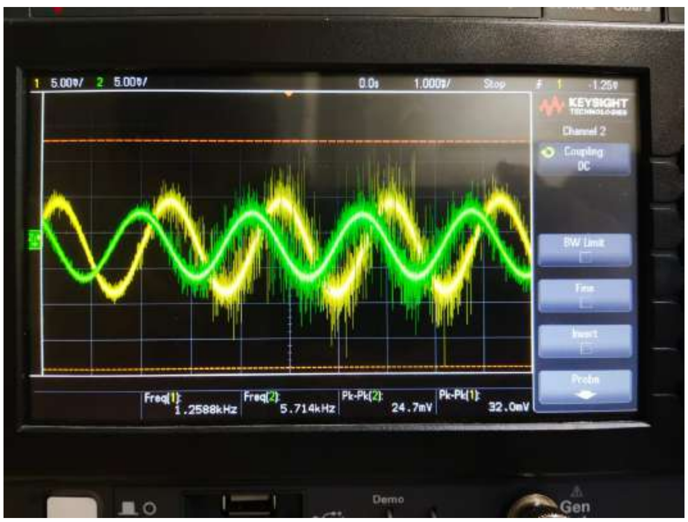

Fig. 40. Final Output

Phase difference observed $\approx$ $(360^o)(3kHz)(72\mu s) = 103.6^o$

Fig. 41. FFT of First Output Wave

Parameters	Simulated	Observed
Oscillator Frequency	97 kHz	100.21 kHz, 100.27 kHz
Oscillator Amplitude (I-Phase)	984.06873 mV_{PP}	1.08V_{pp}
Oscillator Amplitude (Q-Phase)	984.06873 mV_{pp}	1.05 V_{PP}
Input Frequency	100 kHz	100.7 kHz
IF	2.216kHz	1.29kHz & 5.71kHZ
Supply	8V	8V
V_{BIAS}	1.7V	1.7V
C_C	10μF	10μF

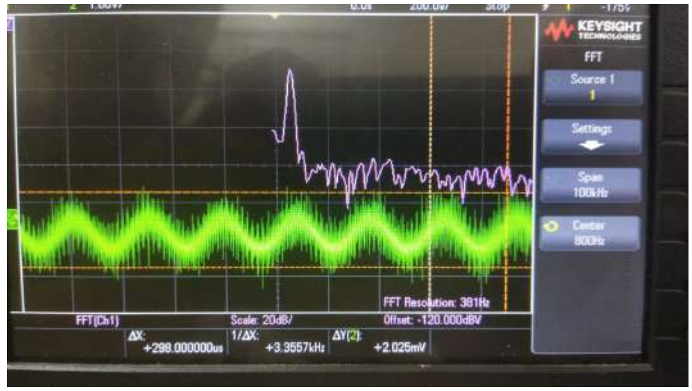

Fig. 42. FFT of Second Output Wave

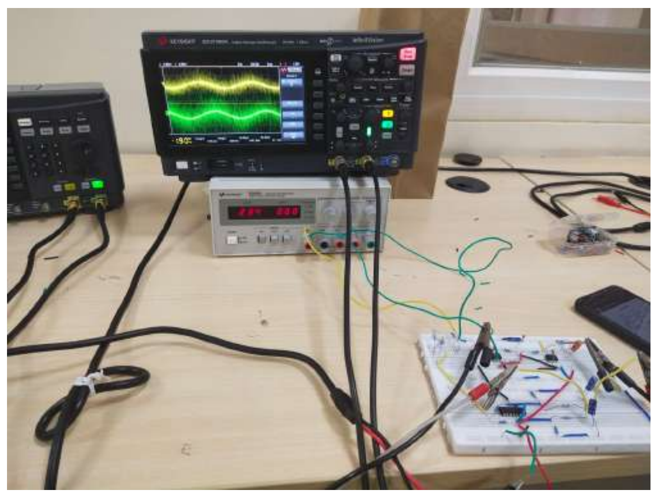

Fig. 43. Measurement Setup

VI. Conclusion

Using fundamental active and passive components, we are able to realize a rudimentary QDC that is able to convert an input signal of 100kHz, into a quadrature signal of frequency in the range 1-5kHz. Even though the first-order prototype can somewhat achieve what we set out to do, the possible fixes in later designs could include:

- Fixing the waveform of the oscillator output that gets distorted due to the slew rate.
- Bringing down the difference between the frequencies of the output sinusoids.
- Lower the harmonic distortion of the output signals.

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"