Prototype of a Quadrature Down Converter

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***Abstract*—The Quadrature Down Converter, abbr. QDC, is a common device employed in modern day wireless receivers, primarily helping with interference mitigation and improvement of communication quality. This report describes the workings of a prototype QDC with working individual blocks, with the given specifications.**

Keywords—quadrature, mixer, oscillator, low-pass

I. INTRODUCTION

Wireless communication, which is so abundant and ubiquitous nowadays, typically requires the transmitted signals in the channel to be of high frequency because of various reasons, including but not limited to noise reduction and error mitigation. The Quadrature Down Converter becomes useful in wireless receivers used in Wi-Fi, Bluetooth, GPS, WLAN and so many other technologies with high frequency raw received signal, to down convert this high frequency into a low frequency output, essentially dropping the carrier and extracting the message into a lower frequency. The prototype implemented in this project makes use of 3 simple blocks: a quadrature oscillator, a mixer (or multiplier), and a low-pass filter. Here is a block diagram for the same:

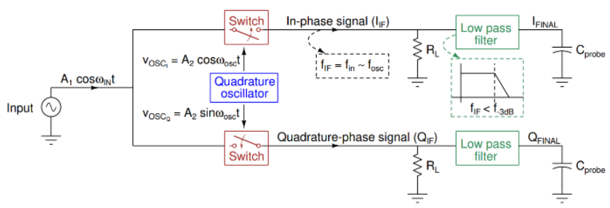


Fig. 1. Block diagram for a Quadrature Down Converter

As shown above, the input signal $v_{in} = A_1 \cos \omega_{in} t$ is mixed with $v_{OSC_I} = A_2 \cos \omega_{OSC} t$ and $v_{OSC_Q} = A_2 \sin \omega_{OSC} t$ to produce in-phase and quadrature-phase signals respectively, with a phase difference of 90°. Mixing of these two signals the same as their product, which may be simplified to:

$$v_{IF_I} = \frac{A_1 A_2}{2}(\cos(\omega_{in} - \omega_{OSC})t + \cos(\omega_{in} + \omega_{OSC})t)$$

$$v_{IF_Q} = \frac{A_1 A_2}{2}(\sin(\omega_{in} + \omega_{OSC})t - \sin(\omega_{in} - \omega_{OSC})t)$$

These signals are fed to a low-pass filter so that only the difference frequency is obtained at I_{FINAL} and Q_{FINAL}, which is quite low, and the very high sum frequency is filtered out.

II. QUADRATURE OSCILLATOR DESIGN

A. *Description of the model*

The quadrature oscillator has two outputs, one generates a sine wave and the other generates a cos wave with the same frequency and amplitude. This oscillator consists of 2 op-amps from which sine and cos waves are generated, as set of resistors and capacitors whose network is fed back to the input of the op-amp, and thus they act as integrator circuits. The noise signal given in the circuit goes into one of the op-amps and gets amplified and upon multiple integrations it becomes a sine wave at saturation. This sine wave output is fed back to another op-amp (integrator) which integrates the signal (sine wave), thus generating a cos wave.

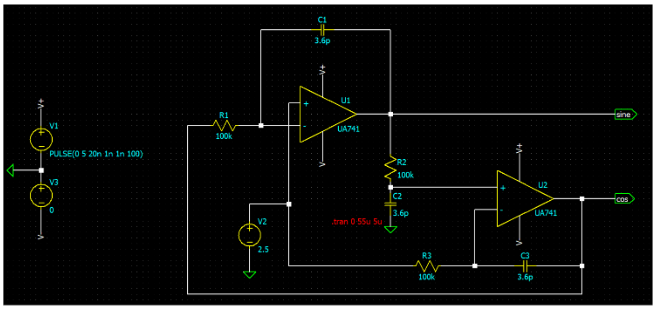


Fig. 2. LTSPICE Circuit for Quadrature Oscillator

$$V_{+_2} = \frac{V_{sine} \times \frac{1}{sC_2}}{R_2 + \frac{1}{sC_2}} = \frac{V_{sine}}{1 + sR_2C_2}$$

$$V_{cos} = V_{+_2}\left(1 + \frac{Z_{C_3}}{Z_{R_3}}\right) = V_{+_2}\left(1 + \frac{1}{sR_3C_3}\right)$$

$$V_{sine} = -V_{cos}\frac{Z_{C_1}}{Z_{R_1}} = -\frac{V_{cos}}{sC_1R_1}$$

Closed loop gain = 1

$$\frac{V_{sine}}{V_{cos}} \times \frac{V_{+_2}}{V_{sine}} \times \frac{V_{cos}}{V_{+_2}} = 1$$

$$\left(-\frac{1}{sR_1C_1}\right) \times \left(\frac{1}{1 + sR_2C_2}\right) \times \left(1 + \frac{1}{sR_3C_3}\right) = 1$$

$$s = j\omega$$

Let $R_1C_1 = R_2C_2 = R_3C_3$

$$\Rightarrow \left(-\frac{1}{j\omega RC}\right)^2 = 1 \Rightarrow \omega = \frac{1}{RC}$$

$$\therefore f_{OSC} = \frac{1}{2\pi RC}$$

B. Topology and Calculations

The resistor and capacitor values in the feedback path are calculated from the relation $f_{out} = \frac{1}{2\pi RC}$, where f_{out} is the output frequency, and R, C are the values of the resistance and capacitance, which are same across all feedback paths.

As the required $f_{out} = 100$ kHz, we fix the resistance to $R = 100$ kΩ, and $C = \frac{1}{2\pi f_{out} R} = 15.9$ pF.

But, we observe less frequency than desired at the output due to op-amp imperfections. To fix this issue, we keep the resistance constant and decrease the capacitance value till the desired f_{out} is achieved. The tweaked value for $C = 3.6$ pF.

C. LTSpice Simulations

The following plots are time domain plots and FFTs of output signals generated by the quadrature oscillator:

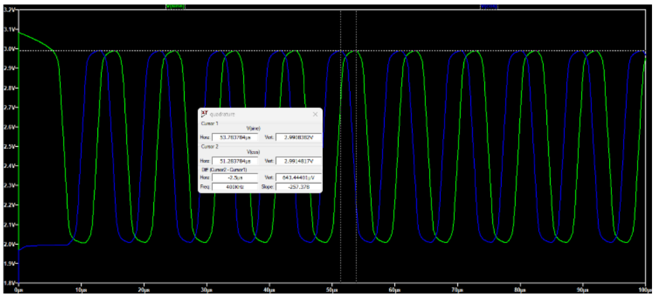


Fig. 3. Transient plots of oscillator outputs showing 90° phase difference between in-phase and quadrature-phase components

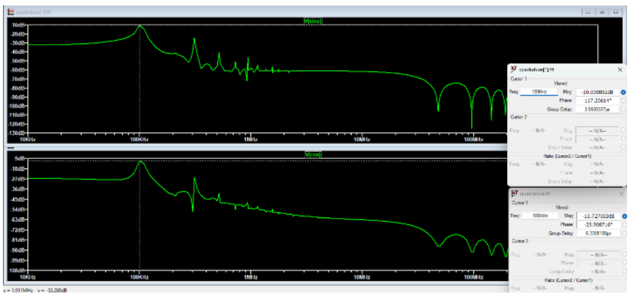


Fig. 4. FFT plots for quadrature-phase (sine) and in-phase (cos) components showing significant peak at 100 kHz

III. Switch (Mixer) Design

A. Description of the model

A mixer or a switch is basically a multiplier which multiplies two signals. A simple mixer consists of a MOSFET, a coupling capacitor, a bias and a load resistor, and a DC supply which is called bias voltage.

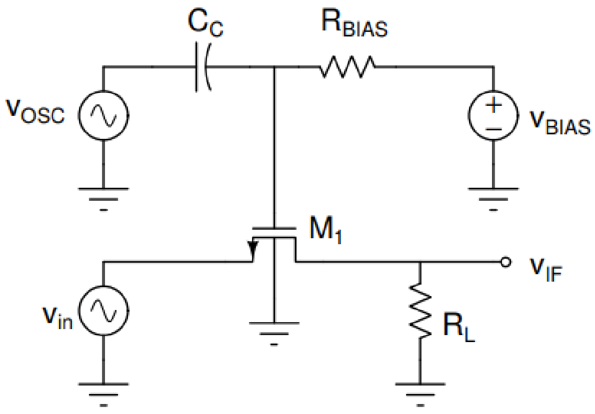


Fig. 5. Mixer design

As we are cascading the output of the quadrature oscillator with the mixer, we use a coupling capacitance in between, which acts as a buffer and prevents disturbance of signals while cascading from one device to another. V_{BIAS} is given to control the switching of the MOSFET. A large bias resistance is given because so that the oscillator signal goes into the gate instead of the bias voltage source. In this design, $R_{BIAS} = 1\ \text{M}\Omega$ and $C_C = 10$ pF. Bias voltage is taken to be just greater than the threshold voltage of the MOSFET so that we can observe a properly on and off switching MOSFET. We will detail an intuitive working of the mixer in the following section for better understanding. The NMOS used in our design has the following characteristics:

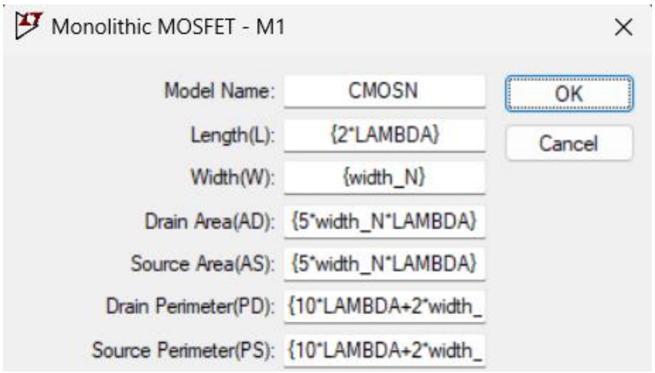


Fig. 6. NMOS parameters (LTSPICE)

The MOSFET described above has an estimated threshold voltage $V_T = 540$ mV, so $V_{BIAS} = V_T = 0.54$ V.

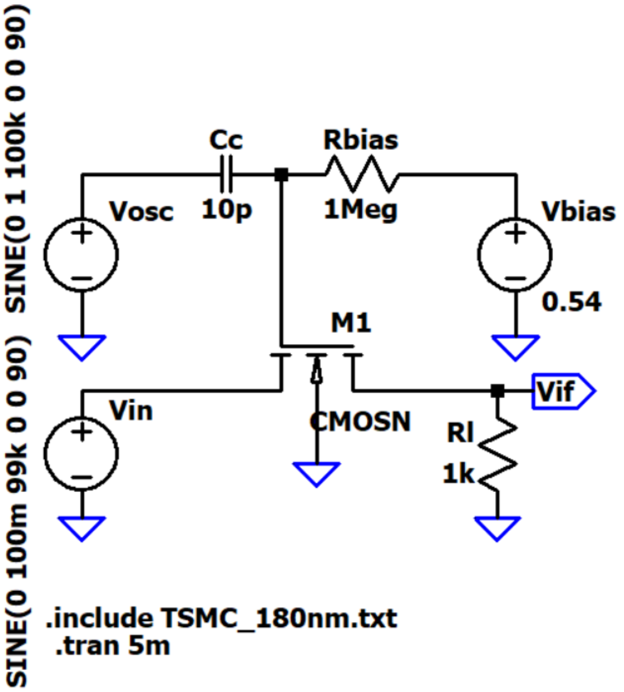


Fig. 7. LTSPICE circuit for Mixer

$$V_{bias} = V_T \,;\, V_D = V_{out} \,;\, V_S = V_{in}$$

$$V_D = \frac{V_S R_L}{R_L + R_{ON}}$$

$$V_{out} = \frac{V_{in}}{1 + \frac{R_{ON}}{R_L}} = \frac{V_{in}}{1 + \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{bias} + V_{OSC} - V_T) R_L}}$$

$$V_{out} = \frac{V_{in}}{1 + \frac{1}{kV_{OSC}}} \qquad \left[k = \mu_n C_{ox} \frac{W}{L} R_L\right]$$

$$\text{If} \quad \frac{1}{kV_{OSC}} \gg 1, \qquad V_{out} = kV_{in}V_{OSC}$$

B. *(Intuitive) Working of Mixer and LTSpice Simulations*

Let's analyze how the mixer works:

- From the circuit, we observe the voltage at the gate terminal to be $V_{GS} = V_{OSC} + V_{BIAS} = V_{OSC} + V_T$
- We know that for cutoff region $V_{GS} < V_T$, so for an NMOS to be on, $V_{GS} \geq V_T$.
- At all positive half cycles of the oscillator signal, $V_{OSC} + V_T \geq V_T$, which means the MOSFET is on and allows passage of signal at source to the drain terminal, where the output of the mixer is derived from.
- For each negative half of the oscillator signal, one can infer from a similar argument as above that the MOSFET is off and the channel from source to drain terminal is cut-off.
- As the frequency of the oscillator signal is large enough, it will be oscillating between positive and negative cycles very quickly, causing the input signal to be mixed with a square wave (generated from the rapidly switching MOSFET) at the mixer output.

The following are the time domain plots and FFTs of the mixer outputs for various input frequencies:

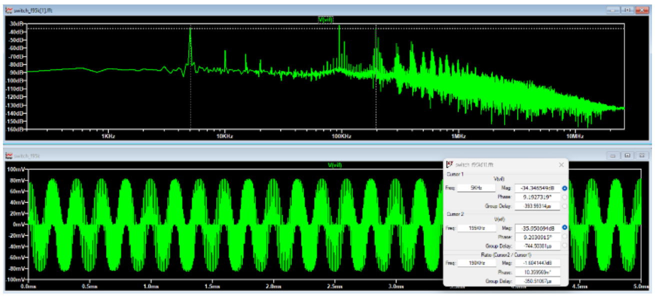


Fig. 8. Transient and FFT plots for f_{in} = 95 kHz mixed with in-phase oscillator component (cos)

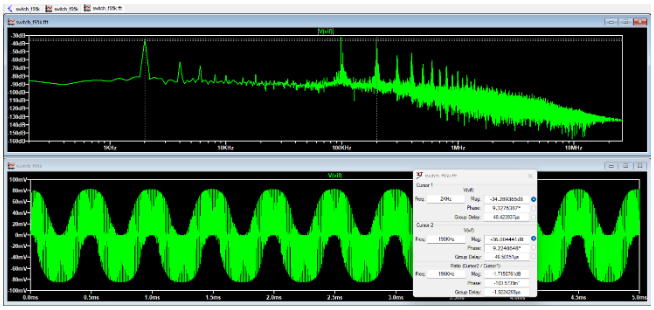


Fig. 9. Transient and FFT plots for f_{in} = 98 kHz mixed with in-phase oscillator component (cos)

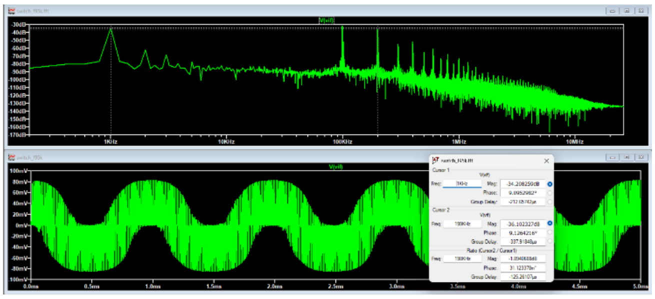


Fig. 10. Transient and FFT plots for f_{in} = 99 kHz mixed with in-phase oscillator component (cos)

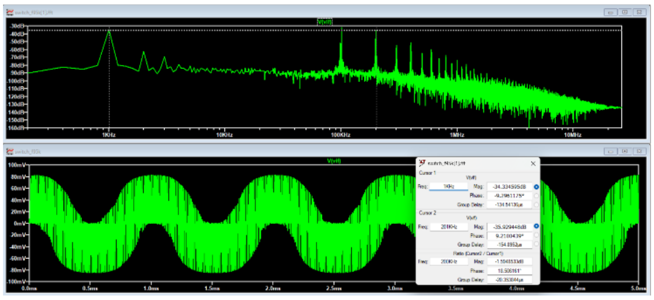


Fig. 11. Transient and FFT plots for f_{in} = 101 kHz mixed with in-phase oscillator component (cos)

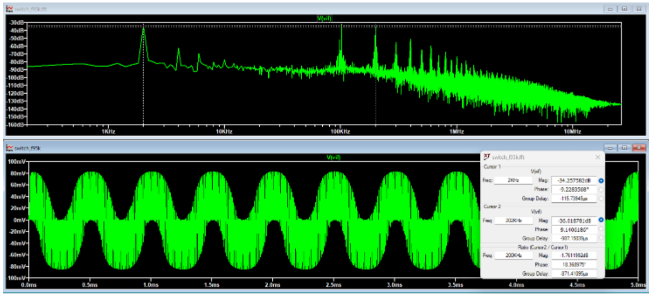


Fig. 12. Transient and FFT plots for f_{in} = 102 kHz mixed with in-phase oscillator component (cos)

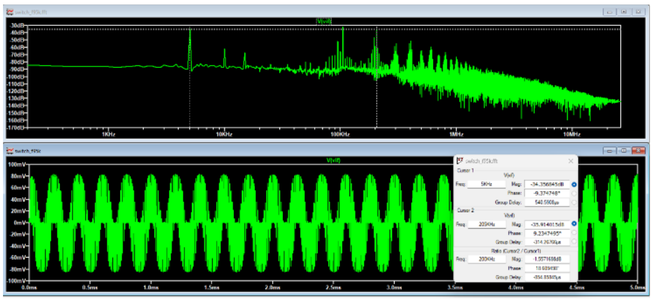


Fig. 13. Transient and FFT plots for f_{in} = 105 kHz mixed with in-phase oscillator component (cos)

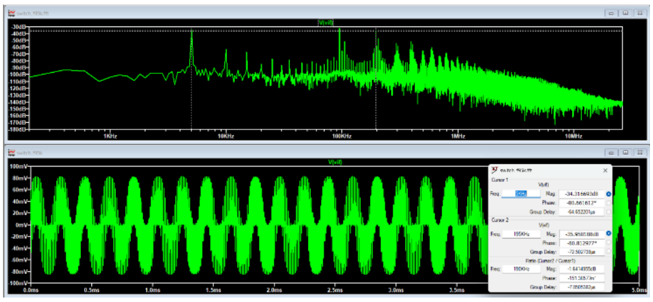


Fig. 14. Transient and FFT plots for f_{in} = 95 kHz mixed with quadrature-phase oscillator component (sine)

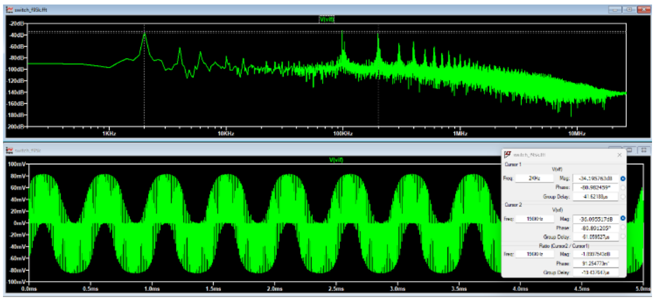


Fig. 15. Transient and FFT plots for f_{in} = 98 kHz mixed with quadrature-phase oscillator component (sine)

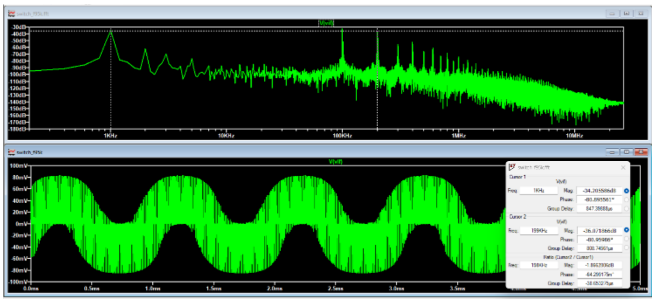


Fig. 16. Transient and FFT plots for f_{in} = 99 kHz mixed with quadrature-phase oscillator component (sine)

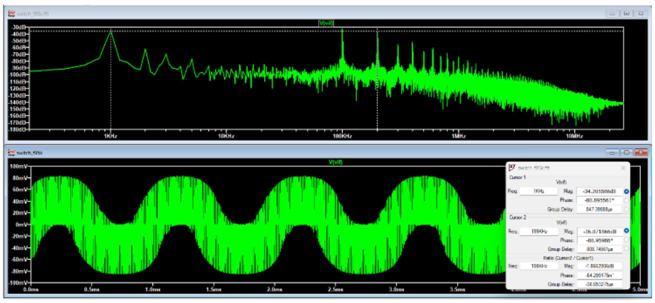


Fig. 17. Transient and FFT plots for f_{in} = 101 kHz mixed with quadrature-phase oscillator component (sine)

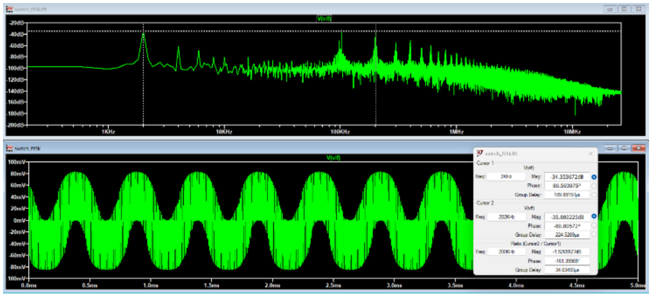


Fig. 18. Transient and FFT plots for f_{in} = 102 kHz mixed with quadrature-phase oscillator component (sine)

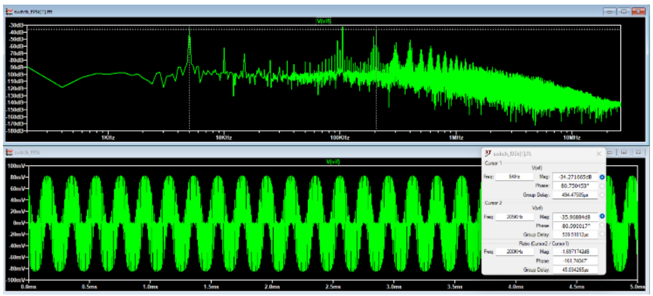


Fig. 19. Transient and FFT plots for f_{in} = 105 kHz mixed with quadrature-phase oscillator component (sine)

From the FFTs, significant peaks are obtained at f_{osc}, $f_{osc} \sim f_{in}$ and $f_{osc} + f_{in}$, which are the major frequency components in the output signal.

IV. Low Pass Filter

A. *Description of the model*

A simple RC low pass filter consists of a resistor and a capacitor with a -3 dB frequency (cut-off frequency) of $\frac{1}{2\pi RC}$. A simple LPF circuit is given below:

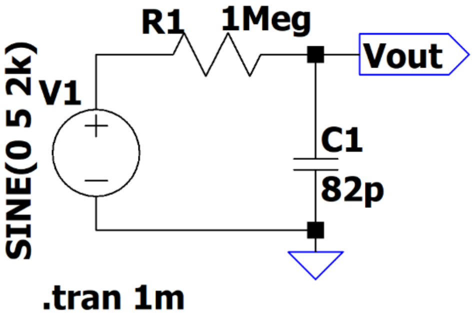


Fig. 20. A simple low-pass RC filter

$$V_{out} = V_{in}\frac{Z_C}{Z_C + Z_R} = \frac{V_{in}}{1 + sCR}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{1}{1 + j\omega RC}$$

$$\text{For } \; j\omega RC \gg 1 \text{ or } \omega \gg \frac{1}{RC}, \qquad A_v \ll 1$$

$$\text{For high frequency,} \qquad V_{out} \to 0$$

$$\text{For } \omega \ll \frac{1}{RC}, \qquad A_v \approx 1$$

$$\text{For low frequency,} \qquad V_{out} \to V_{in}$$

B. *Working of LPF and LTSpice Simulations*

When a signal is passed into an RC filter it attenuates (decreases the amplitude of) the input signal to a higher extent if the input frequency is greater than the cutoff frequency of the filter, than when the input frequency is lower than the cutoff frequency. The cut-off frequency of the RC filter is determined by the value of $\frac{1}{2\pi RC}$, where R, C are the values of resistance and capacitance used. And if the input signal's frequency is less than the cutoff frequency, the input signal is less attenuated and the output looks almost same. For designing a low pass filter with -3 dB frequency of 2 kHz, we choose R, C values such that the product $RC = \frac{1}{2\pi f_{-3dB}}$. On choosing $C = 82$ pF, $R \approx 1$ MΩ.

The following are time domain and bode plots for the specified low-pass filter:

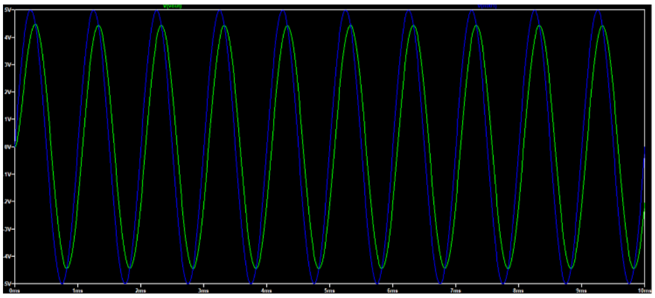


Fig. 21. Transient plot for $f_{in} = 1$ kHz

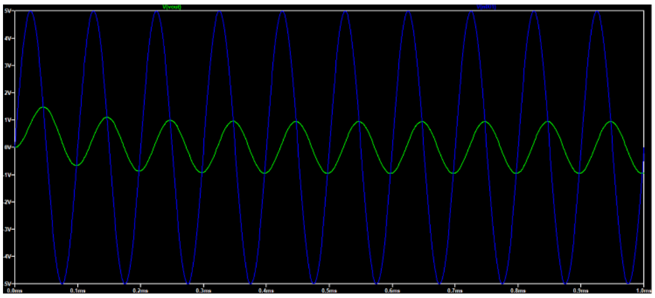


Fig. 22. Transient plot for $f_{in} = 10$ kHz

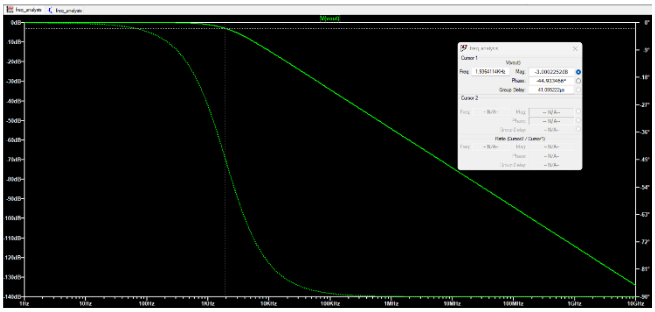


Fig. 23. Frequency analysis (bode plot) for low-pass filter with $f_{-3dB} = 2$ kHz

C. *Working of LPF along with Mixer*

As we know, after mixing the oscillator and input signals, we send that signal into a low pass filter which removes all unnecessary frequency components and gives out respective in-phase and quadrature-phase components with frequency down-conversion.

As the mixer output consists of two frequencies $f_{in} \pm f_{OSC}$ the low pass filter removes the frequency component $f_{in} + f_{OSC}$ and gives a signal with only $f_{in} \sim f_{OSC}$ at the output with certain extent of attenuation which depends on the cut-off frequency of the filter.

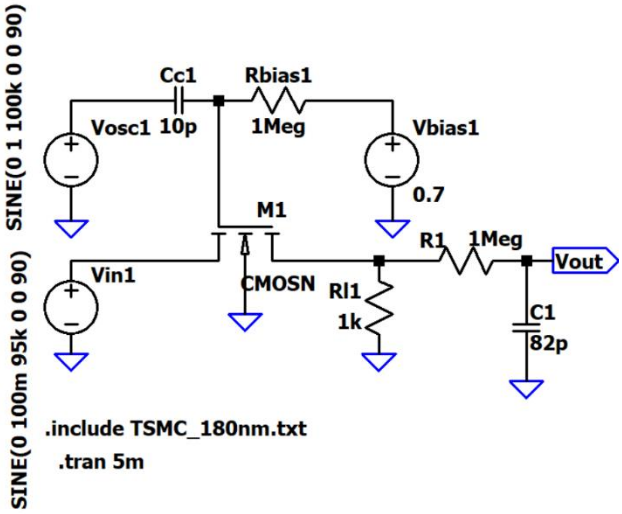


Fig. 24. LTSPICE circuit for Mixer and Low Pass Filter

D. *LTSPICE simulations of LPF and Mixer circuit*

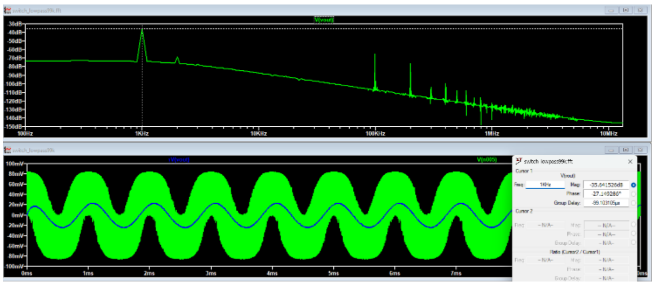


Fig. 25. Mixer and LPF outputs' transient plots, with LPF's output's FFT plot showing clear peak at 1 kHz

V. COMPLETE CIRCUIT PROTOTYPE DESIGN

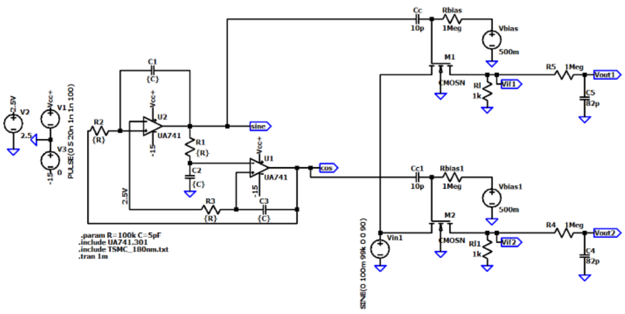


Fig. 26. LTSPICE circuit for the complete QDC prototype

A. *Transient Simulations in LTSPICE*

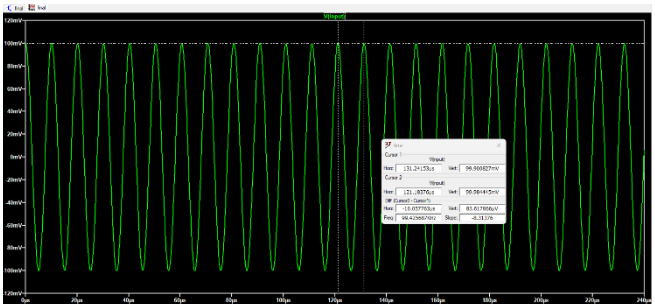


Fig. 27. Transient plot for $f_{in} = 99$ kHz

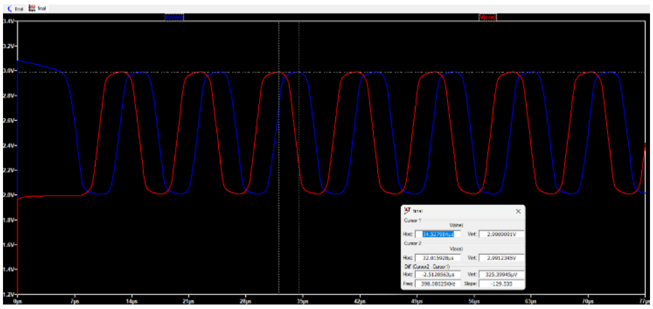


Fig. 28. Transient plots for in-phase and quadrature-phase components of the oscillator, showing 90° phase shift

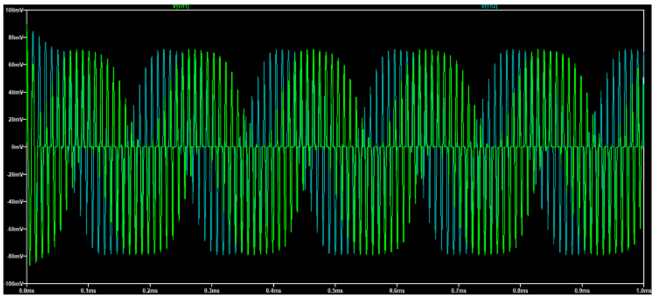
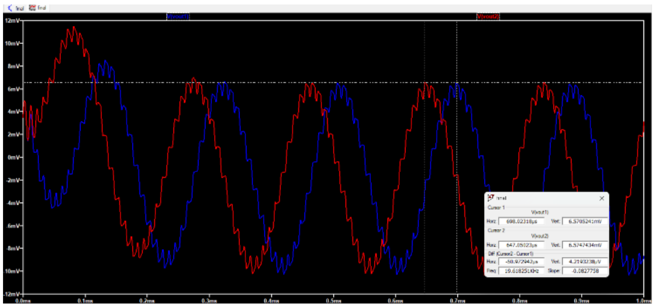


Fig. 29. Transient plots for mixer outputs for both sine and cos components



Fir. 30. Final output plot from low pass filter showing in-phase and quadrature-phase components of input signal with phase difference of 90°

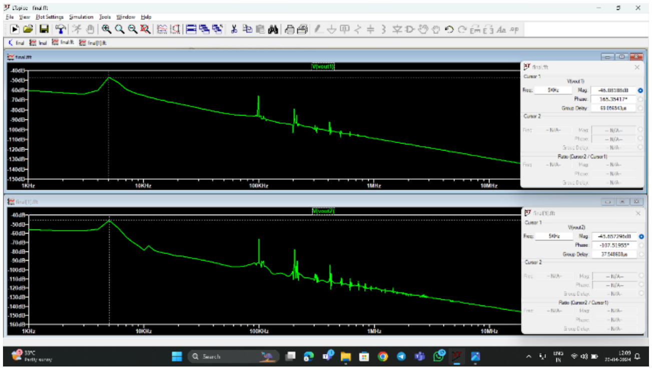


Fig. 31. FFT Plots of the final output signals

VI. Hardware Run

A. Quadrature Oscillator

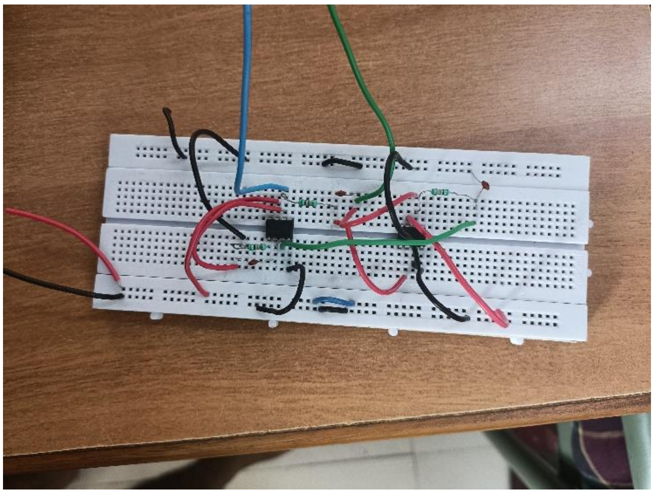


Fig. 32. Quadrature Oscillator Circuit

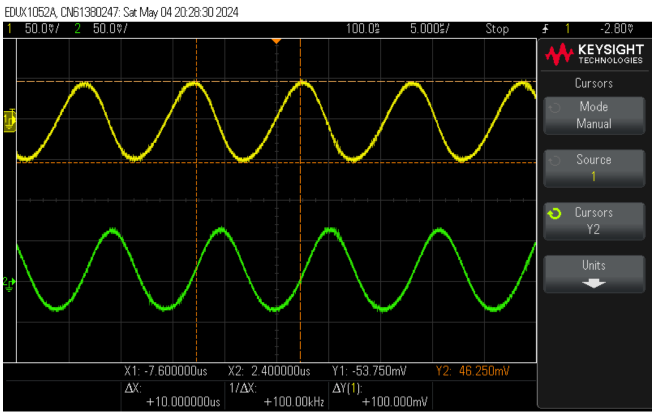


Fig. 33. Transient plots for oscillator outputs

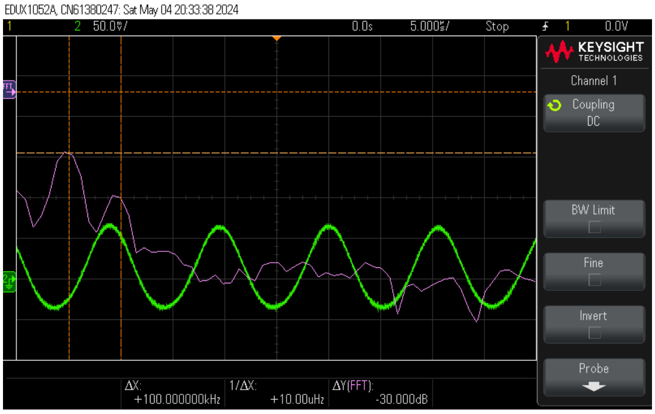


Fig. 34. FFT plot for in-phase component

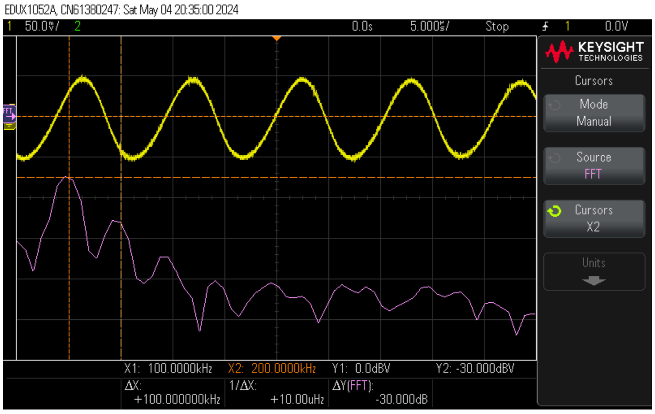


Fig. 35. FFT plot for quadrature-phase component

As seen in Fig. 33, the obtained output amplitude is 50 mV_{PP}, while the desired amplitude is 1 V_{PP}. To correct this, we used a noninverting amplifier circuit at the output of the oscillator, and fed its input to the mixer.

B. Switch (Mixer)

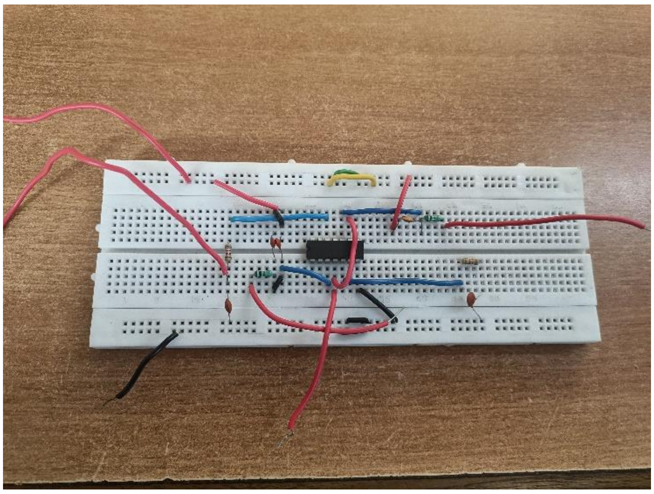


Fig. 36. Switch Circuit

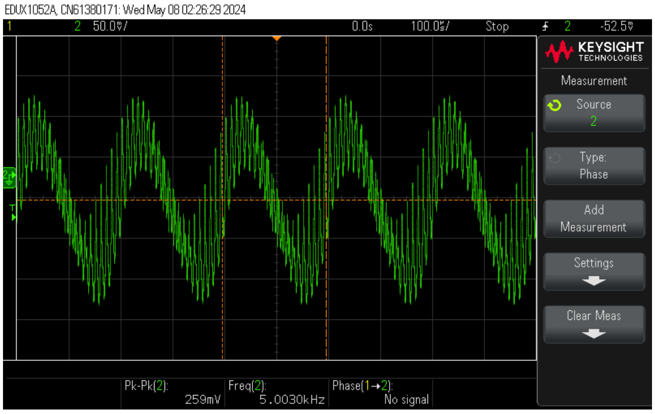


Fig. 37. Transient plot for mixer output (f_{in} = 95 kHz)

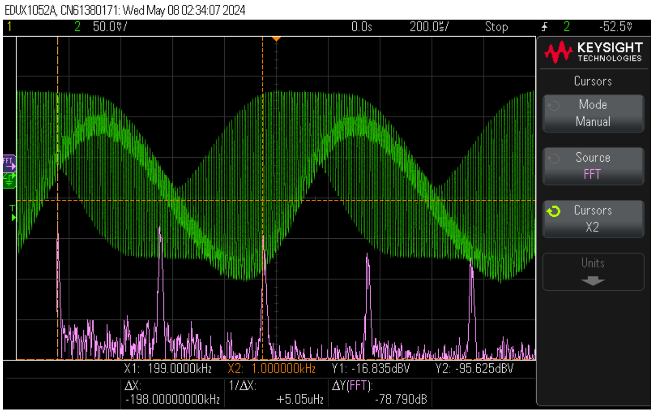


Fig. 38. FFT Plot for mixer output (in-phase), showing significant peaks at sum and difference frequencies (f_{in} = 99 kHz)

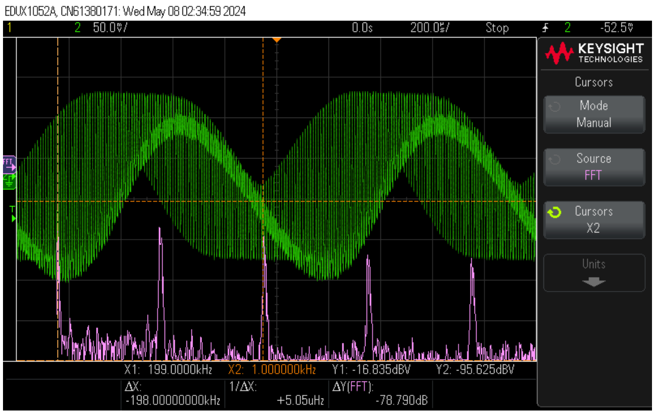


Fig. 39. FFT Plot for mixer output (quadrature-phase), showing significant peaks at sum and difference frequencies (f_{in} = 99 kHz)

C. Low Pass Filter

The hardware resistance and capacitance values had to be altered, since a parallel probe capacitance came into play with picofarads of LPF capacitance. It reduced the effective capacitance, thus increasing the cutoff frequency of the filter. So, we had to choose $C = 10$ nF in order to neglect probe capacitance, making $R \approx 8.2$ kΩ.

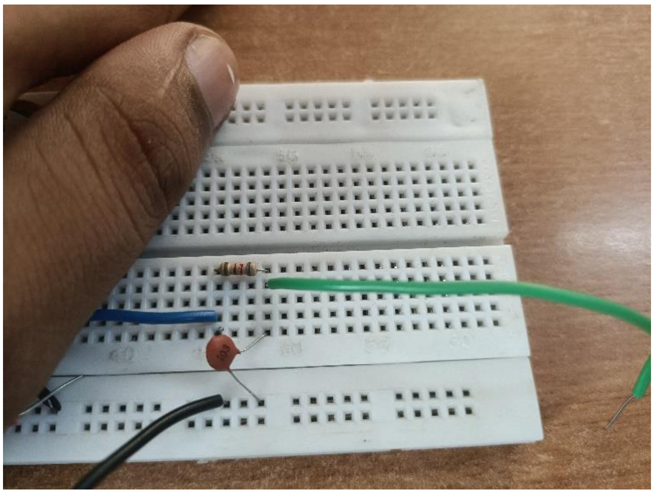


Fig. 40. Low Pass Filter Circuit

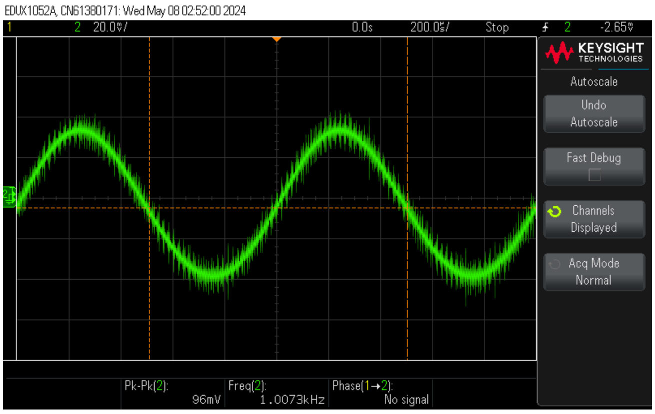


Fig. 41. Transient plot for final output component

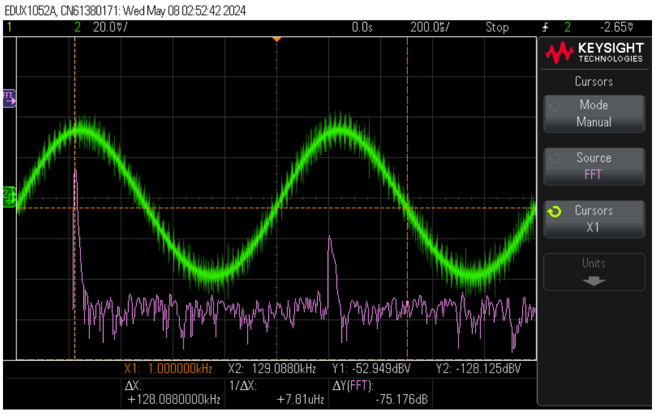


Fig. 42. FFT plot for final output component (f_{in} = 99 kHz)

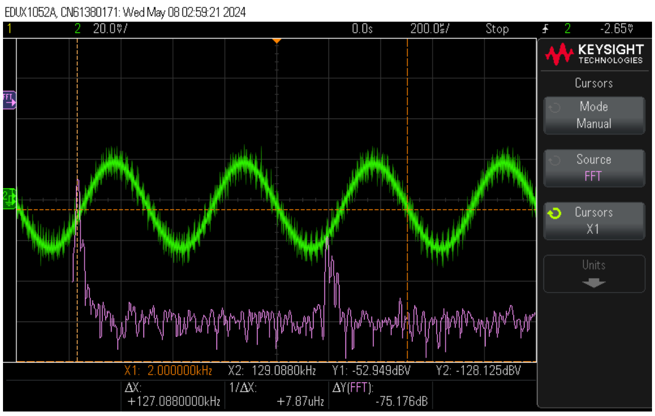


Fig. 43. FFT plot for final output component (f_{in} = 98 kHz)

D. Performance Analysis

Parameter	Values	
	Simulated	***Measured***
Oscillator Frequency	100 kHz	98 kHz
Oscillator Amplitude (I-phase)	1 V_{PP}	1 V_{PP}
Oscillator Amplitude (Q-phase)	1 V_{PP}	1 V_{PP}
Input frequency	99 kHz	99 kHz
IF	1 kHz	1 kHz
Supply	5 V	16 V
V_{BIAS}	0.54 V	0.94 V
C_C	10 pF	10 pF

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