Quadrature Down Converter

AEC Project, Spring 2022

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***Abstract*—A simple model of Quadrature Down Converter along with its individual components such as Quadrature Oscillator for generating 90° phase shifted sinusoidal signals, a mixer circuit component, to multiply two input signals, and a simple RC Low Pass Filter, is presented.**

***Index Terms*—Quadrature, Oscillator, Filter, Low-Pass, Mixer, FFT, Op-Amp, MOSFET**

I. Introduction

Quadrature Down-conversion is common in today's world and has wide applications in interference mitigation and helps in improving the quality of communication in wireless communication. The aim is to convert a signal of some given high frequency, to a lower frequency signal.

The components used in our model of QDC are (a) Quadrature Oscillator (b) Mixer (c) RC Low-Pass Filter. The goal of this project is to realize such a QDC and analyze its working, simulations and applications in real life.

II. Technology used

The mixer uses 90nm CMOS technology for simulations. All of the simulations are done in LT-Spice and actual experiments are on Keysight EDUX1052G Digital Storage Oscilloscope. The following table summarises the parameters of the NMOS used in mixer circuit :-

Parameter	*Value*
Model Name	CMOSN
Length (L)	0.09μm
Width (W)	1.8μm
Drain Parameter	4.5μm
Source Parameter	4.5μm
Drain Area	0.81pm^2
Source Area	0.81pm^2

Device Parameters for NMOS used

III. Device Modelling

Before using any device, it is necessary to model it and verify its working. We now model and characterize the devices used in out circuit, to find out the parameter values such as V_T and verify the behaviour of the devices used.

A. Mosfet Characterisation

To characterise the mosfet, we plot the graph of I_D *vs* V_{GS} for the nmos used and obtain the value of V_T (Threshold Voltage) from the graph, which will be of major use while designing the mixer for QDC.

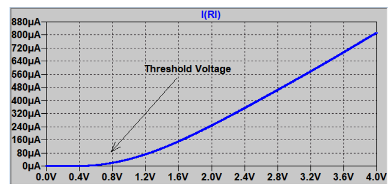

Fig. 1. I_D versus V_{GS} graph for the NMOS used

The value of V_T was found out to be 0.665V

B. Op-Amp Characterisation

The op-amps use in the Quadrature Oscillator circuit is **UA741** and is a non-ideal one. Therefore the plot of V_{out} vs V_{in} is plotted on LT-Spice and its nature and gain is verified against theoretical values.

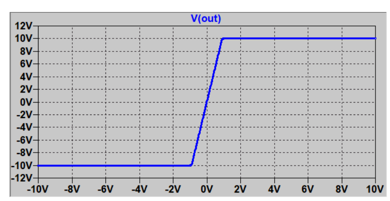

Fig. 2. V_{out} versus V_{in} graph for the op-amp used

IV. Oscillator Design

A. Circuit and Working

The function of designing a Quadrature Oscillator is to obtain two $\frac{\pi}{2}$ phase shifted sinusoidal waves using no external input source but the noise present in the environment.

We know that the noise present in the environment is substantially large to be amplified and used for generating sinusoidal signals. This fact is exploited in Quadrature oscillator where a sin and a cos wave are generated using 2 non-inverting op-amps set to satisfy the criteria for oscillation.

Figure 3 depicts the circuit used for the quadrature oscillator

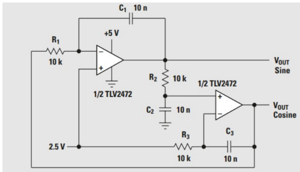

Fig. 3. Quadrature Oscillator Circuit

Oscillation occurs in the given circuit because :-

- The magnitude of the loop gain is greater than 1
- Total Phase shift around the whole loop is $2k\pi$

This phase shift through A_2 is +90° as it is a pure integrator and inverter, the next phase shift of -90° occurs through the R_3 and C_3 voltage divider circuit, summing up to a total phase shift of 0°. The necessary condition for proper working of this circuit is:-

$$R_1C_1 = R_2C_2 = R_3C_3 = RC \ \ (say) \tag{1}$$

The signal received at node N is fed into A_1 as a non-inverting integrator, the output of which is directly integrated using a simple integrator to give cosine version of the same signal.

A very high amplitude of output signal leads to distortion on the waveform itself, and thus, it is necessary to maintain the amplitude of the output signal regulated using regulator circuits. However, if the loop gain is very small, this may result in the oscillations to stop/slow-down resulting in undesirable waveform at the output. Note that the circuit oscillates correctly only at a certain frequency given by :-

$$f_{osc} = \frac{1}{2\pi RC} \tag{2}$$

B. Simulations

The circuit is implemented in LT-Spice with $R = 1.6M\Omega$ and $C = 0.1pF$ and the output of the oscillator is plotted.

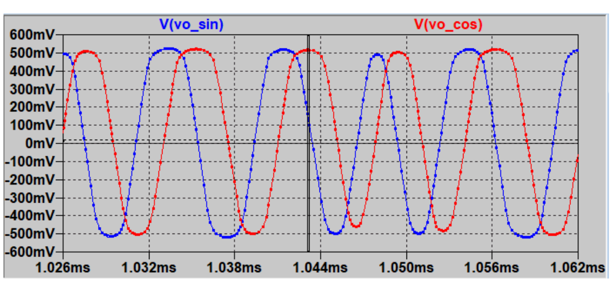

Fig. 4. Quadrature Oscillator Output

Observations : It can be clearly observed from the annotations that when one of the output is zero, the other is at its peak, therefore the phase different between both of them is approximately 90°. Also the waveform of both the waves is almost sinusoidal if not perfectly.

V. MIXER DESIGN

The purpose of mixer circuit is to multiply the given 2 input signals. An 90nm NMOS is used for this purpose where the oscillator signal generated from the quadrature oscillator is applied at the gate terminal of the nmos and input signal is applied at the source terminal. The output is taken from the drain where the expression of output signal is given by :-

$$V_I = \frac{A_1A_2}{2}\left(\cos\left(w_{in} - w_{osc}\right)t + \cos\left(w_{in} + w_{osc}\right)t\right) \tag{3}$$

$$V_Q = \frac{A_1A_2}{2}\left(\cos\left(w_{in} + w_{osc}\right)t - \sin\left(w_{in} - w_{osc}\right)t\right) \tag{4}$$

The following circuit is implemented to realize mixer/switch function in this project :-

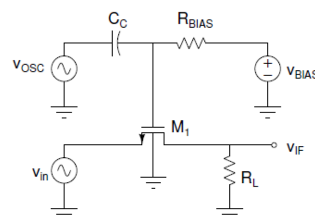

Fig. 5. Mixer/Switch Circuit

To observe the switching action of the MOSFET, the value of V_{bias} is kept around V_T (0.665V) of the MOSFET, so that a slight positive/negative change in V_{in} causes the MOSFET to go on/off as according to the condition

$$V_{gs} \lessgtr V_T \tag{5}$$

The purpose of the capacitor C_c is to block the AC component of V_{osc} in the DC analysis whereas R_{BIAS} prevents the DC component of V_{BIAS} from interfering in the AC analysis. By properly setting the values of C_c R_{BIAS}, V_{BIAS}, and R_L, we can observe proper mixer output.

The output of such a mixer circuit majorly contains the sum and difference of frequencies of inputs while their FFT shows presence of harmonics of those frequencies too.

The circuit is simulated in LT-Spice and the output graph for the mixer is observed.

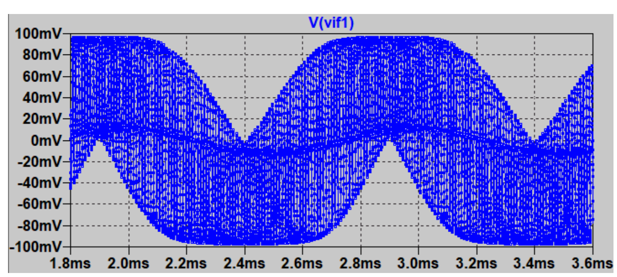

Fig. 6. Mixer/Switch Output

The graph obtained is verified theoretically using mathematical tools and is found correct.

Also, for given values of $f_{osc} = 100kHz$ and $f_{in} = 99kHz$ the FFT of the Output is plotted to observe the various frequencies present in the output signal, and it is found that peak occurs at high f_{osc} and two almost equal peaks occur at values $f_{osc} + f_{in}$ and $f_{osc} - f_{in}$ as shown in the figure.

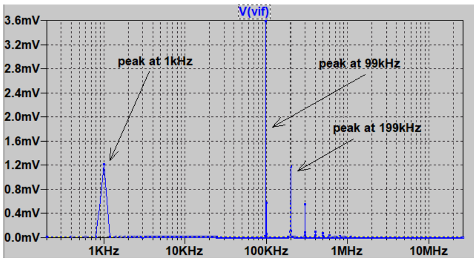

Fig. 7. FFT of the output of the Mixer

It is observed that the frequency visible in the envelope of the output is $f_{osc} - f_{in}$ and is of lower value than that observed inside the envelope. The frequency to which we intend to down-convert our signal into is this envelope frequency, the final step to which is given in the next component of our circuit.

VI. RC Low-Pass Filter

The output generated from Mixer circuit is fed to a low pass filter with pre-set values of R and C (to define -3dB frequency) so filter out the high frequency components from the input and the output contains the final down converted signal.

A. Circuit and Working

A simple RC Low pass filter circuit is used for this purpose.

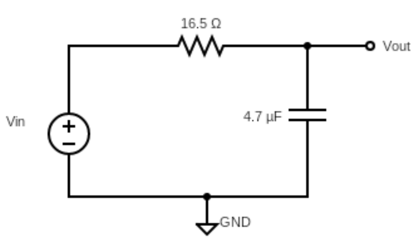

Fig. 8. RC Filter Circuit

The filter is designed to set the -3dB cutoff frequency as 2kHz and so the values of R and C are chosen as $R = 16.5k\Omega$ and $C = 5nF$, to give cutoff frequency

$$f_{cutoff} = \frac{1}{2\pi RC} = \frac{10^6}{486} = 2.053Hz \tag{6}$$

Plotting the frequency analysis for the LPF circuit, we get the following graph :-

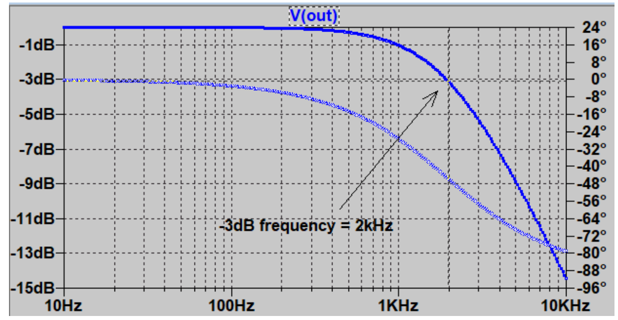

Fig. 9. Frequency response of the RC Low-Pass Filter

Transient Response for some frequencies We shall now observe transient response for $f_{in} = 1kHz$ and $f_{in} = 10kHz$. It is clearly seen that the magnitude of output signal is considerably lowered when the frequency is 10kHz ($f_{in} > f_{cutoff}$) while the amplitude remains negligibly altered when frequency is 1kHz ($f_{in} < f_{cutoff}$). Such transient responses are plotted as below:-

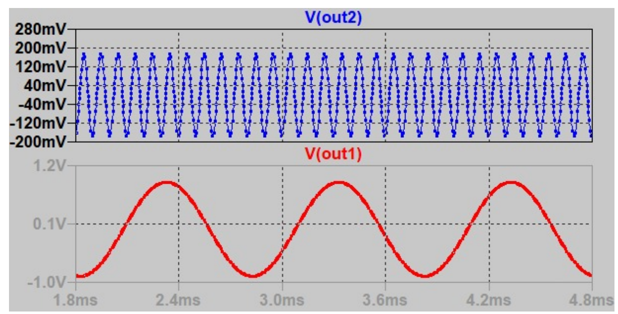

Fig. 10. Frequency response of the RC Low-Pass Filter

Observation : It is observed that V_{pp} of the output is significantly lowered for $f_{in} = 10kHz$ (V_{out1}), while the magnitude remains negligibly altered for $f_{in} = 1kHz$ (V_{out2}).

VII. Complete QDC

The individual components of the Down Converter are assembled together to obtain the prototype of the Quadrature Down Converter. The main function of the QDC is to convert a signal of some given high frequency to a signal of lower frequency thereby, down converting it. The steps performed in this process are :-

- Generating two 90° out of phase sinusoids V_{osc}(In Phase) and V_{osc}(Quadrature Phase)
- Taking the V_{osc} signal and multiplying it with the original signal to produce a mixed signal with various frequencies.
- Passing the mixed signal to a RC Low-Pass filter to get the signal with reduced frequency.

This process is depicted in the following system diagram accurately.

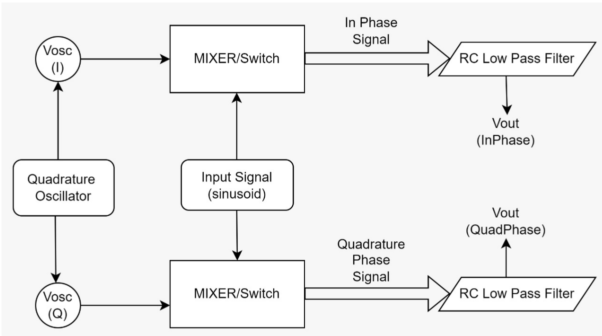

Fig. 11. System Diagram for Quadrature Down Converter

The Down Converter is implemented in Hardware and the results are obtained as follows :-

A. Quadrature Oscillator

The quadrature oscillator is implemented in hardware, with R=1.8MHz and C=5.6pF, to give oscillation frequency :-

$$f_{osc} = \frac{1}{2\pi RC} = 15.79kHz \tag{7}$$

Sinusoidal signal is obtained as output with frequency of 15.94Hz, thereby verifying our calculations.

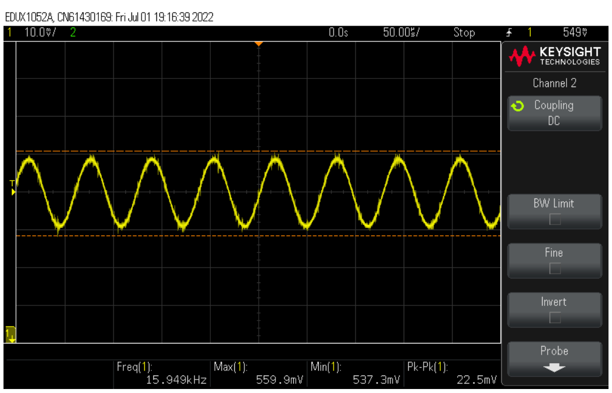

Fig. 12. Oscillator Output for $f_{osc} = 15.79kHz$

B. Mixer Output

The mixer circuit is implemented and given 2 sinusoidal signals to multiply. Where $f_{osc} = 100kHz$ and $f_{in} = 95kHz$. According to equation 3, the resultant should contain frequency components of $f_{in} + f_{osc}$ (195kHz) and $f_{in} - f_{osc}$ (5kHz). The same is observed in the output.

It can be observed that the envelope is of lower frequency (5kHz) while the frequency present inside of envelope is of the higher frequency (195Hz). We intend to generate a sinusoidal signal of the envelope frequency (5kHz). This can be obtained by removing high frequency components on the wave i.e. passing the signal to a low pass filter. The individual frequency components can be observed in the FFT of the mixer output as seen in figure 14.

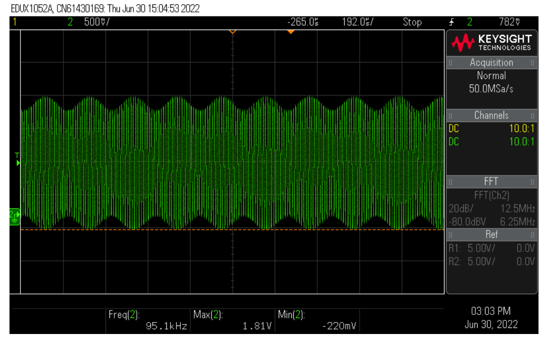

Fig. 13. Transient output of the Mixer

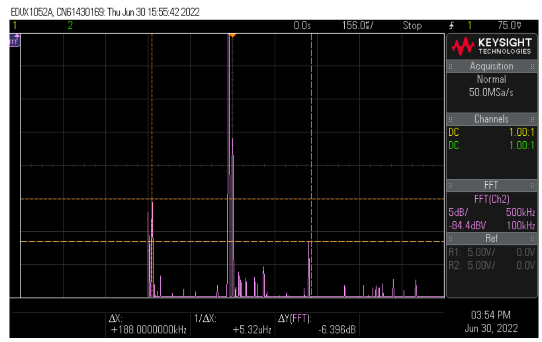

Fig. 14. FFT of the Mixer Output

Observations : Peaks of almost equal magnitude can be observed at 5kHz and 195kHz representing the 2 major frequency components found in equation 3. Further, frequencies of 95kHz as well 100kHz show peaks. Note that this FFT matches the theoretical FFT obtained in figure 7.

C. RC Low-Pass Filter

First, to characterize the Low-Pass Filter, its frequency response is plotted and -3dB cutoff frequency is found out. A filter of f_{cutoff} of 2kHz is first designed to verify the working, for which the bode plot is obtained as follows:-

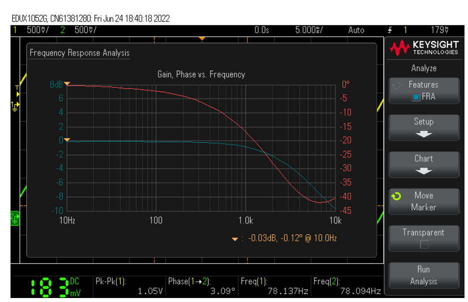

Fig. 15. Frequency Response of 2kHz Low Pass Filter

However, for our given values of f_{in} and f_{osc}, we design a low-pass filter with $f_{cutoff} = 15kHz$ (R=1.1kΩ, C=10nF), to retain the 5kHz component and filter out the rest. By passing the mixer output to a low pass filter, we can filter out the high frequency components from the signal and obtain a down converted signal as shown in the DSO image below :-

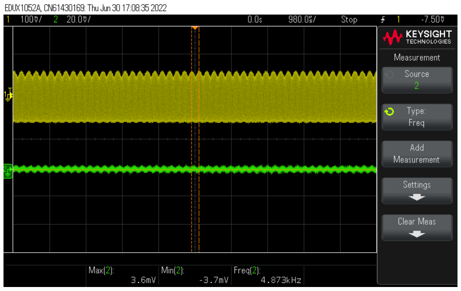

Fig. 16. Transient Response of the RC Filter (Yellow-input and Green-Output)

It can be seen from the image that the frequency of the final output is 4.873kHz, thereby verifying out theoretical calculations with experimental results. On simulating, it is seen that the final output signal has frequency that of the envelope of the mixer output as shown :-

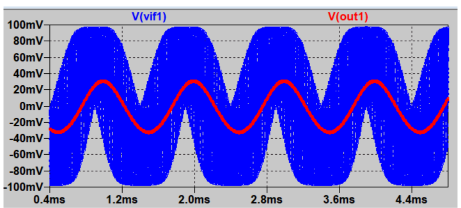

Fig. 17. Final output as the envelope of the mixer output

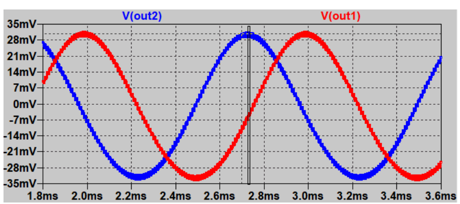

Fig. 18. Final outputs of the down-converter 90° out of phase

Note : Similar graphs of Quadrature Component is also observed except for a phase shift of $\frac{\pi}{2}$.

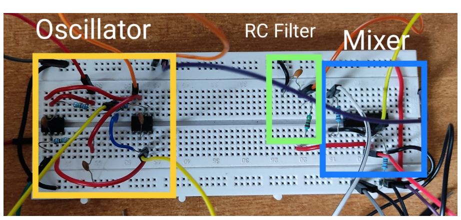

Fig. 19. Circuit Implemented in Hardware

VIII. Comparison between Simulated and Actual Values

We now summarise the values of various parameters used/observed in a tabular form for comparison as below:-

Parameter	***Simulated***	***Measured***
V_{BIAS}	0.665V	0.710V
Oscillator Amplitude (V_{pp})	$1V$	$22V$
Oscillator Frequency (f_{osc})	100kHz	15.79kHz
$R \cdot C$ (for Oscillator)	$0.16\mu s$	$10.08\mu s$
Input Frequency (f_{in})	99kHz	95kHz
Supply (V_{DD} and V_{ss})	$\pm 3V$	$\pm 3V$
V_T for NMOS	0.665V	0.710V
C_c in Mixer	$1\mu F$	10nF
cutoff frequency for Filter (f_{cutoff})	2kHz	15kHz

Conclusion

The report shows that a simple quadrature down converter can be designed for given values of parameters and the theoretical as well as simulation verification of its working and behaviour are also discussed.

References

The following references were taken for the making of this project :-

- Ron Mancini, Design of op amp sine wave oscillators, Texas Instruments Incorporated
- Asad A. Abidi, Direct-Conversion Radio Transceivers for Digital Communications, IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 30, NO. 12, DECEMBER 1995
- Adel S Sedra and Kenneth C. Smith, Microelectronic Circuits, Theory and Applications, 6^{th} ed, Oxford University Press.
- Behzad Razavi, Design of Analog CMOS Integrated Circuits, Tata McGraw-Hill
- Science Direct- Mixer Circuits and Quadrature Oscillators.