Quadrature Down Converter

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***Abstract*—This document aims to explore the nature and working of a Quadrature Down Converter (QDC) and depict the process of implementation of the same as per assigned specifications.**

***Index Terms*—Quadrature Down Converter (QDC), modulation, demodulation, up-conversion, down-conversion, switch/mixer, low-pass filter (LPF), local oscillator (LO), digital storage oscillator (DSO)**

I. INTRODUCTION

With the advent of Digital Era, the semiconductor industry has seen a boost unparalleled that in-fact provides an impetus to the Era.

In the quest of striving for a better (in terms of cost and speed), newer (in terms of innovation) and faster (in terms of processing and compliance with other devices) technologies, the semiconductor industry has relentlessly given the world unimaginable processing and communicating power. Pertaining to this very nature of the industry, it is the field of communications that has benefited the most – with the development of diodes, BJTs, MOS devices, Op-Amps, which have given birth to certain highly beneficial circuitry. This, to say the least, has indeed led to the development of the domain of Analog Electronics.

It is one such contribution in the field of analog electronics that this project paper aims to explore and further state the procedure to implement – the **Quadrature Down Converter (QDC)**. The QDC has various applications (primarily in wireless communications) such as radio astronomy, electronic surveillance, broadband communications, microwave instrumentation, wireless receivers (Rx), Wi-Fi, WLAN to name a few.

The motive of the wireless communication technology is to carry and message signal from the transmitter (Tx) and transmit it across the channel to the receiver's end (Rx). Although the process seems simpler, it is far from being so in reality. The process faces a problem, i.e., the message signal is generally a low frequency signal and transmitting such low frequency signals over long distances is not feasible (due to factors such as atmosphere, power, length of antenna, etc. that contribute to the cost of transmitting, attenuation, etc. of the signal). Therefore, a process named **modulation** is adopted wherein the message signal is modulated with a **carrier** wave and carried to a higher frequency spectrum after which it is transmitted along the channel. This method of carrying the signal to a higher frequency spectrum is called **frequency up-conversion**. At the Rx's end, a high frequency modulated signal is received. Now, for a certain circuitry, there is a band of frequency within which it can operate efficiently. Beyond the specified bandwidth of operation, the device does not deliver as it was intended to. Therefore, there arises a need to **demodulate** or **down-convert** the received signal. As the name suggests, demodulation is basically reversing (so to say) the effect of modulation, and the device used to achieve so is called a **frequency down-converter**.

A transmitted signal (m_t) is often obtained as the superimposition of two base-band signals (one is **in-phase** (m_{tI}) with the message signal and the other one is 90°out of phase with the message signal - called the **quadrature phase** (m_{tQ}) signal). The following equation shows the same:

$$m_t(t) = m_{tQ}(t)\sin(2\pi f_t t) + m_{tI}(t)\cos(2\pi f_t t)$$

Therefore, when the receiver obtains the modulated signal, it first needs to demodulate it (or down-convert it) in order to make it usable for the next concerned circuitry. This involves multiplying the incoming signal with in-phase and quadrature-phase signals and then passing them through the LPF to obtain the corresponding components from the transmitted signal. In our case, we achieve the multiplication of two signals by implementing a mixer or switch configuration as discussed further in the paper.
Fig. 1 captures the basic working of the transmission channel under discussion:

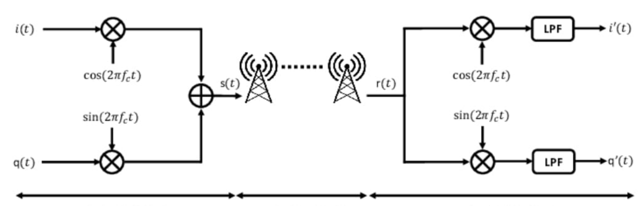

Fig. 1. Communication system depicting modulation at the transmitter's end and demodulation at the receiver's end

The above technique works because of the **orthogonality** property of signals, which says that for signals that can be broken down into sinusoidal components (using some technique like Fourier Series Analysis), we can obtain a particular sinusoidal component of that signal by multiplying the signal with that particular sinusoidal. This multiplication results into the required sinusoidal and all other components are filtered out due to their orthogonality with the concerning sinusoidal. The following equations denote why demodulation using the above technique works:

we have,

$$m_t(t) = m_{tQ}(t)\sin(2\pi f_t t) + m_{tI}(t)\cos(2\pi f_t t)$$

Therefore, by multiplying $m_t(t)$ by $2\cos(2\pi f_t t)$, we get,

$$2m_t(t)\cos(2\pi f_t t) = 2m_{tQ}(t)\sin(2\pi f_t t)\cos(2\pi f_t t) + 2m_{tI}(t)\cos(2\pi f_t t)\cos(2\pi f_t t)$$

And, now applying the trigonometric formulae, we finally get,

$$2m_t(t)\cos(2\pi f_t t) = m_{tQ}(t)\sin(4\pi f_t t) + m_{tI}(t)\cos(4\pi f_t t) + m_{tI}(t)$$

Now after passing this through the LPF, it is evident that we will obtain the required in-phase component. Similarly, by multiplying the transmitted signal with $2\sin 2\pi f_t t$, and then passing it through the LPF, we will obtain the quadrature phase component.

The purpose of this paper is to capture the analysis, design and implementation of this entire process where, the flow is as follows:

- The quadrature oscillator (or local oscillator LO) generates the two in-phase and quadrature-phase signals to be multiplied with the transmitted signal
- The mixer comes next, which performs the function of multiplying the transmitted and LO-output signals
- The LPF is the final section of the circuit which ensures that the final output obtained contains the signal of required bandwidth (the down-converted one)

Fig. 2 captures the process in its entirety:

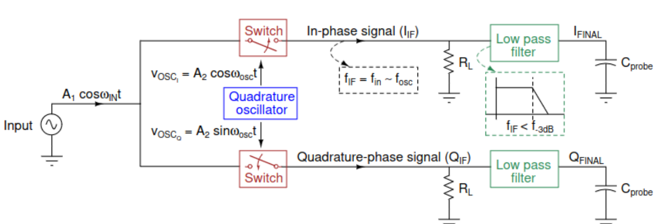

Fig. 2. Flow Diagram for QDC

II. Design and Analysis of Individual Components of the QDC

The discussions regarding the design and analysis of the circuitry used in the making of the QDC are limited by the fact that the paper aims to present them for a relatively lower band of frequencies (in the order of a few hundreds of kilo-Hertz).

A. Quadrature Oscillator (LO)

A **Quadrature Oscillator** is a device that is used to generate, as the name suggests, two outputs, namely - **In-Phase (IF)** and **Quadrature Phase (QF)**. Intuitively, the electronic component that is appropriately suited for the task is an Op-Amp because of its operational qualities as well as its ability to generate oscillatory outputs. One more reason to support the choice of using op-amps to construct the desired circuit is due to the fact alongside the afore-mentioned properties, the most fundamental or core usage of the op-amp is to amplify the input based on the principles of differential amplification.

These properties together serve as the basis for designing the Quadrature Oscillator :

- *Amplification* - Enables us to produce the output of required strength
- *Frequency* - Enables us to choose the frequency at which the feedback loop of the op-amp performs oscillations by selecting the appropriate values of R and C
- *Operational Qualities* - This particular property of op-amps helps us to generate the in-phase output and then use it using an integral or differential circuit (of op-amps) to generate the quadrature phase output
- *Phase Shift* - Helps us to obtain a 0°phase shift to generate a sine wave and a 90°phase shift to generate a cos wave

1) Design and Analysis of LO: The design of a Quadrature Oscillator consists of mainly 4 stages:

- *Wien Bridge* - The Wien's bridge is frequency sensitive network consisting of 4 resistors and 2 capacitors as shown in the Fig. 3.

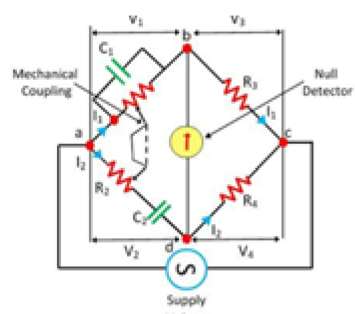

Fig. 3. Wien Bridge

When the bridge is in the balanced condition, the potential of the node B and C are equal, i.e., the (V_1) = (V_2) and (V_3) = (V_4) The phase and the magnitude of (V_3) = $(I_1)(R_3)$ and (V_4) = $(I_2)(R_4)$ are equal, and they are overlapping each other. The current (I_1) flowing through the arm BD and the current (I_2) flowing through (R_4) is also in phase along with the $(I_1)(R_3)$ and $(I_2)(R_4)$. (Fig. 4)

At balance condition,

$$\left(\frac{R_1}{1 + j\omega C_1 R_1}\right) R_4 = \left(R_2 - \frac{j}{\omega C_2}\right) R_3$$

On equating the real part,

$$R_1 R_4 C_2 = R_2 C_2 R_3 + R_3 C_1 R_1$$

$$\frac{R_1 R_4 C_2}{R_1 R_3 C_2} = \frac{R_2 C_2 R_3}{R_1 R_3 C_2} + \frac{R_3 C_1 R_1}{R_1 R_3 C_2}$$

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} + \frac{C_1}{C_2}$$

On comparing the imaginary part,

$$R_3 R_2 \omega^2 C_2 C_1 R_1 = R_3$$

$$R_2 \omega^2 C_2 C_1 R_1 = 1$$

$$\omega = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

By substituting the value of $\omega = 2\pi f$,

$$f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

- *Op-Amp 1* - The terminal B of the Wien Bridge is connected to the inverting terminal of the op-amp whereas the terminal D is connected to the non-inverting terminal of the op-amp. The op-amp amplifies the difference in potential between the terminal B and D.
- *Feedback* - The terminal A of the Wien's bridge is used as a feedback for the circuit. As the Wien's Bridge is a frequency sensitive circuit, it lets only a single frequency given by the formula above to survive and all other frequencies die out. Therefore, the output of the op-amp is a sine wave with this particular frequency.
- *Integrator Op-Amp* - The output from the op-amp is fed into the inverting terminal of an another op-amp which acts as an integrator. Hence, it integrates the sine wave from the first op-amp and gives us a cos wave required for the quadrature operation.

2) LTSpice Simulations: **Refer to Fig. 4 and Fig. 5**

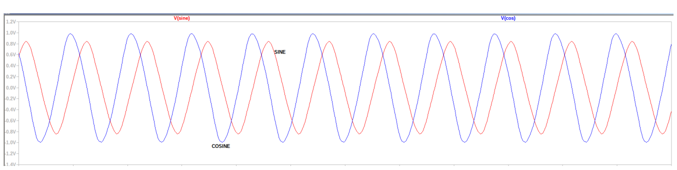

Fig. 4. Output of the Oscillator: Red colored wave corresponds to that of Sine and the Blue colored wave is of Cosine

3) Practical Circuit and Output of Quadrature Oscillator: **Refer to Fig. 6 and Fig. 7**

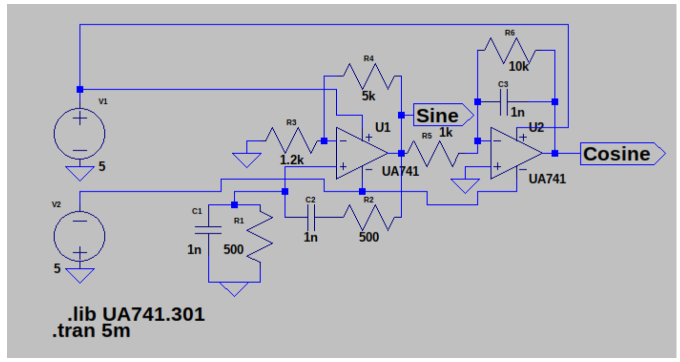

Fig. 5. Simulated Circuit of the oscillator that generated the waveforms in the above figure

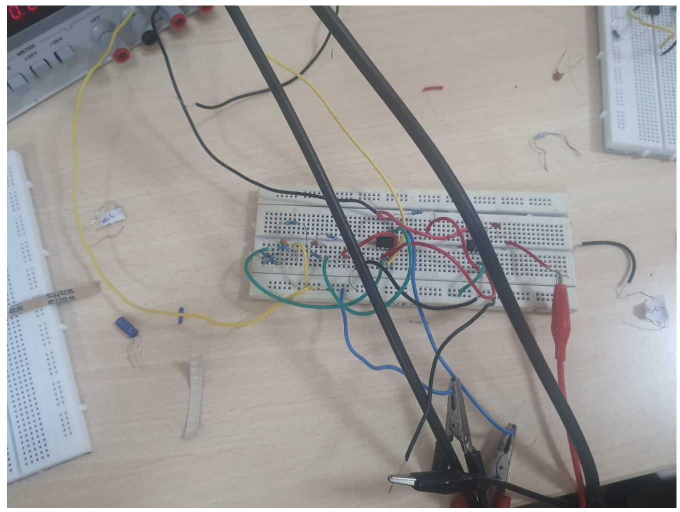

Fig. 6. Practical Oscillator Circuit

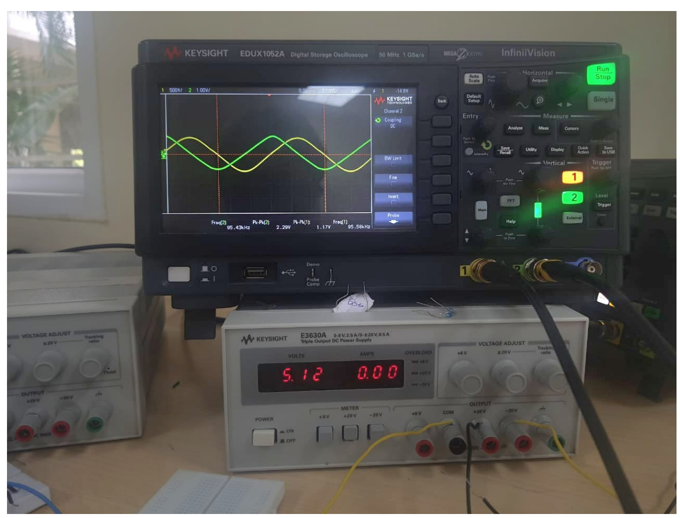

Fig. 7. Practical Oscillator Output
NOTE: The yellow plot is the plot for sine wave and the green plot is the plot for the cosine wave

B. Mixer (switch)

As depicted in the previous few diagrams, the output from the local oscillator (LO) is fed into the mixer (or the switch) along with the input signal so as to obtain the outputs, namely the in-phase signal (**IF**) and quadrature-phase signal (**QF**). The outputs are received as per the equations previously mentioned and are then passed through the LPF for further refinement.

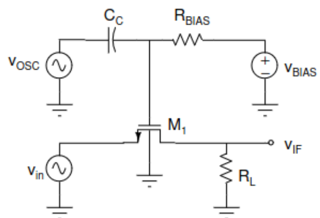

Fig. 8. Reference Circuit for the mixer/switch configuration

1) Design and Analysis of Mixer: The basic motive of the mixer or the switch is to take two signals as inputs - one that periodically turns it on and off (we will refer to it as the **triggering signal**) and the second which gets channelised to the output (**transmitted signal**) node only when the device is on. The result of is a product of the two signals. This process, more technically known as **demodulation** or **down-conversion**, helps us in reversing the effect of **modulation**.

The best electronic component that can be of utmost help here is the NMOS device. The reason behind choosing this device is because of the ease that it poses when used as a switch.

In our case, we have used the output from the LO as the triggering signal which is applied at the gate terminal of the NMOS device and the transmitted signal (in our case the signal from the DSO) is applied at the source terminal of the device. The output, known as the **Intermediate Frequency (IF)** output is taken at the drain terminal. (As shown in Fig. 8).

Principle behind the working of MOSFET as a switch-The MOSFET has three regions of operation - Cut-off region, Triode (Linear) region and Saturation region. Since amplification is not an aspect that we wish to exploit in the implementation in discussion, the regions of our interest therefore, in the NMOS device are the Cut-off and Triode region.

Therefore, the following biasing conditions are needful :

1) $V_{GS} < V_T$ (for the Cut-off region)
2) $V_{DS} < V_{GS} - V_T$ (for the Triode region ; will always be satisfied)

The switch is said to be **on** in the Cut-off region and **off** in the Triode mode.

In the circuit used by us, $v_{GS} = V_{BIAS} + v_{osc}$ (where "osc" stands for oscillator). For the required operation of the NMOS, the $V_{BIAS} \cong V_T$, so the switch will only turn on when $v_{osc} > 0$ and remain off otherwise, as the equations below show :

$$v_{GS} = V_{BIAS} + v_{osc}, \text{ which implies}$$

$$v_{GS} = V_T + v_{osc}$$

The first biasing condition is required for "on" and "off" behavior. Thus,

$$v_{GS} < V_T$$
$$V_T + v_{osc} < V_T$$
$$v_{osc} < 0$$

which shows that the device will be "off" during the negative half cycle of v_{osc}, thereby exhibiting the switching behavior.

Further, the value of R_{BIAS} has to be chosen as high as possible so as to prevent the DSO output (transmitted signal) from passing into the biasing branch which may hamper with proper biasing. Also, the value of C_C will be as low as possible so as to prevent attenuation of the incoming signal. (We have chosen $R_{BIAS} =$ and $C_C =$).

Now, when all these conditions are satisfied, the mixing of the signals happens in accordance with the following equations:

$$v_{IF_I} = v_{in} + v_{lo_I} = \frac{A_1 A_2}{2}(\cos(\omega_{in} - \omega_{lo}) + \cos(\omega_{in} + \omega_{lo})$$
$$v_{IF_Q} = v_{in} + v_{lo_Q} = \frac{A_1 A_2}{2}(\sin(\omega_{in} - \omega_{lo}) + \sin(\omega_{in} + \omega_{lo})$$

where v_{IF_I} is the in-phase output and v_{IF_Q} is the quadrature-phase output, v_{in} is the output from the DSO, and v_{lo_I} and v_{lo_Q} are the in-phase and quadrature phase outputs of the LO.

2) LTSpice Simulations: **Refer to Fig. 9 and Fig. 10**

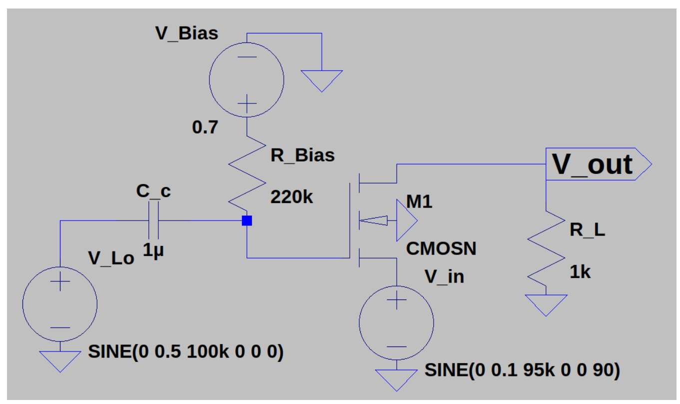

Fig. 9. Circuit for the Mixer/Switch

3) Practical Circuit and Output of Mixer: **Refer to Fig. 11 and Fig. 12**

C. Low-Pass Filter

A Low Pass Filter (LPF) is a circuit made of a resistor and a capacitor which lets the components of the input signal having a frequency lower than a certain cut-off frequency to pass to the output but filters out the high frequency components of the input signal. The value of the cut-off frequency is determined by the resistance and capacitance values.

1) Design and Analysis of Low Pass Filter: In the QDC, the outputs from the mixers, v_{lo_I} and v_{lo_Q} consists of mainly 2 components: the low frequency message signal ($m_t(t)$) and

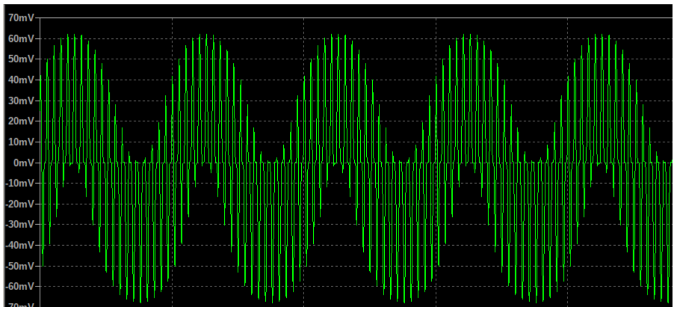

Fig. 10. The output of the mixer/switch. Evidently, the output is a product of the two signals in discussion

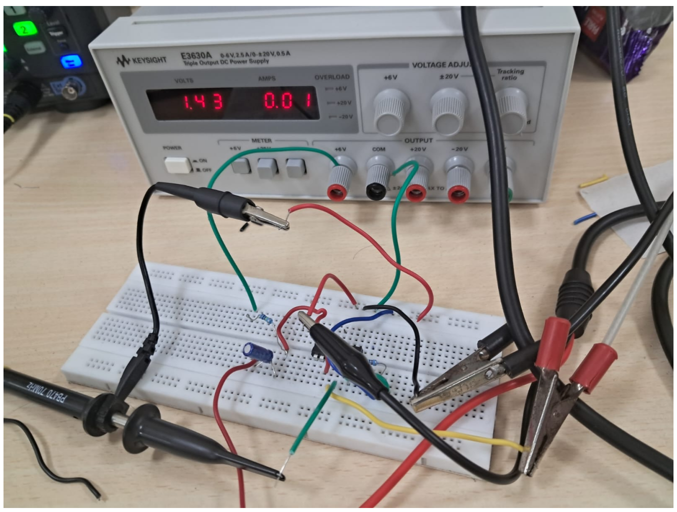

Fig. 11. Practical Mixer Circuit

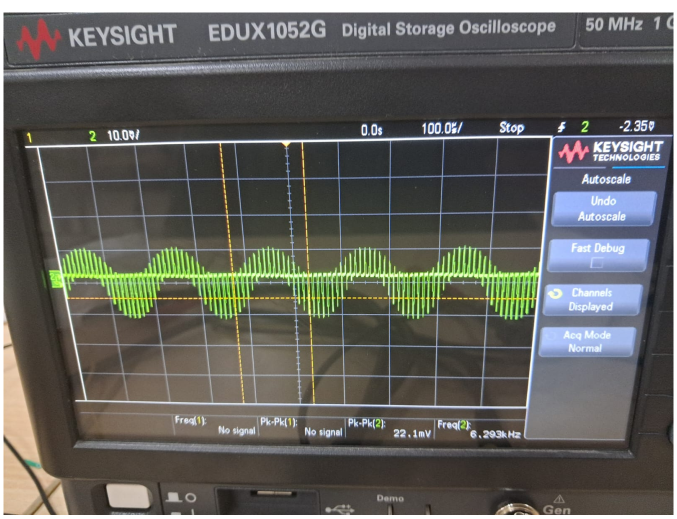

Fig. 12. Practical Mixer Circuit

the high frequency carrier wave. The signal that we want at the output is the message signal. Therefore, we pass the output of the mixers through an LPF with a cut-off frequency of 2kHz. In this way, we obtain the in-phase message signal ($m_{tI}(t)$) and the quadrature phase message signal ($m_{tQ}(t)$) at the final output.

Cut-off frequency:

$$f_c = 1/2\pi RC$$

At the cut-off frequency the ratio:

$$20log(_{V_{out}/V_{in}}) = -3dB$$

Due to this, the cut-off frequency is also known as the -3dB frequency.

2) LTSpice Simulations: **Refer to Fig. 13 and Fig. 14**

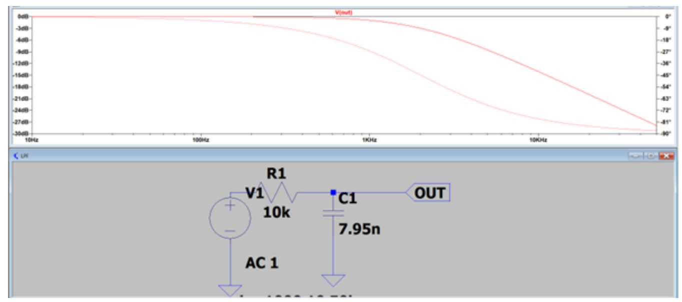

Fig. 13. Passive LPF
The above image shows the circuit of a passive LPF and the its Frequency analysis. NOTE: The solid line represents the magnitude whereas the dotted line represents the phase.

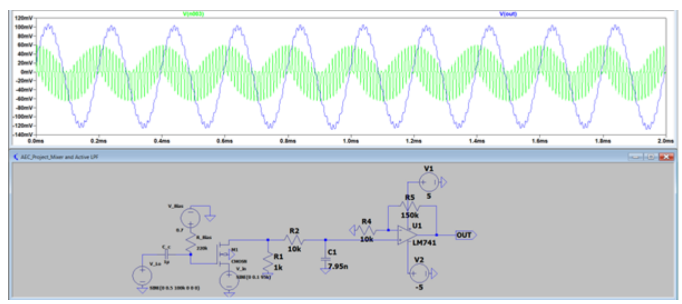

Fig. 14. Mixer and Active LPF
The above image shows the combined circuit of the mixer and the active LPF and the plot for the output of mixer(in green) and the final output after passing through the LPF(in blue)

3) Practical Circuit and Output of LPF: **Refer to Fig. 15 and Fig. 16**

III. Quadrature Down Converter (QDC)

1) Need for Quadrature Operation:

- *Increase in Bandwidth* - The combination of two amplitude modulated signals into a single channel, doubling the bandwidth of a system.
- *Increase Data Rate* - The carrier signal can carry a higher number of bits, resulting in a high data rate.

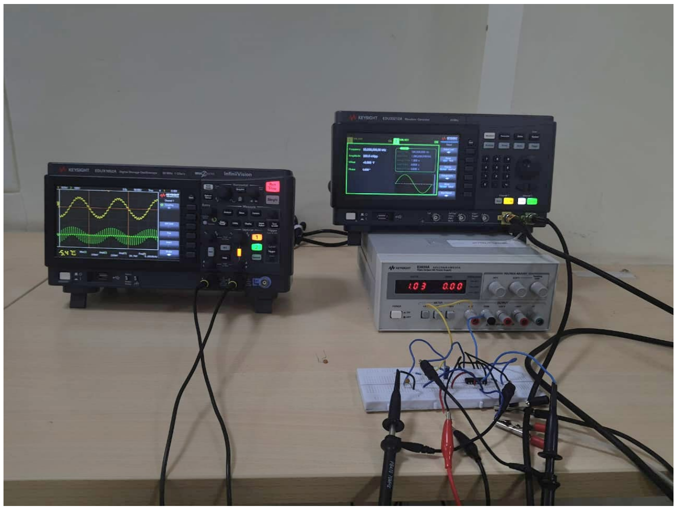

Fig. 15. Practical Circuit set-up of Mixer and LPF combined

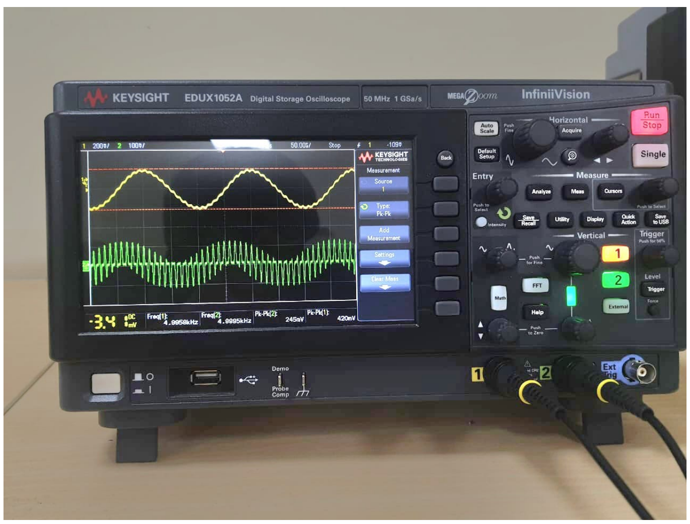

Fig. 16. Practical Circuit Output of Mixer and LPF Combined
NOTE: The green plot shows the output of the mixer and the yellow plot shows the output after passing through the LPF

- *Reduces Attenuation* - Noise immunity is high, causing less noise interference during data transmission
- *Lower Probability of Error*

2) Working of the QDC: The following set of points provide a step-by-step explanation regarding the working of the Quadrature Down Converter: (The deeper aspects of the individual components have been explored and analysed in the previous sections)

- *Quadrature Oscillator* - This forms the foundational step in the process of demodulation or down-conversion because the generation of in-phase and quadrature-phase happens at this stage. The two op-amps used here, along with the appropriate combinations of passive elements like resistors and capacitors help in establishing an oscillator and an integrator thereafter. This configuration generates the appropriate sinusoids at required frequencies (in our case the required freq is 100kHz)
- *Mixer or Switch* - The second component in the hierarchy of QDC circuit which takes in two input signals and provides a product of both. The output to the mixer is called the Intermediate Frequency (IF) and contains two frequency components - lower frequency which is the difference of the frequencies of both the inputs and the higher frequency which is the sum of the frequencies of the inputs. The mixers are two in quantity - one for in-phase demodulation and the other for the quadrature-phase demodulation
- *Mixer or Switch* - This is the final stage of the QDC. Here is where the signal is literally down-converted. The outputs obtained from the mixer are passed through a series combination of a resistor and a capacitor which form a low-pass filter. This ensures that only the lower-frequency component of the Intermediate Frequency signal is finally obtained as the output. It filters out or highly attenuates the higher–frequency components.

Therefore, after passing and getting processed through all the steps mentioned above, we finally obtain the final two components that we intended to find - the in-phase and quadrature-phase.

3) LTSpice Simulations: **Refer to Fig. 17 to Fig. 20** for the simulation results

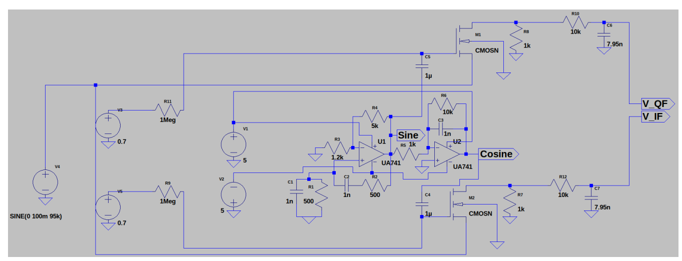

Fig. 17. The final circuit implemented by combining all the individual components discussed previously in the paper
This is the **Quadrature Down Converter** (QDC) Circuit

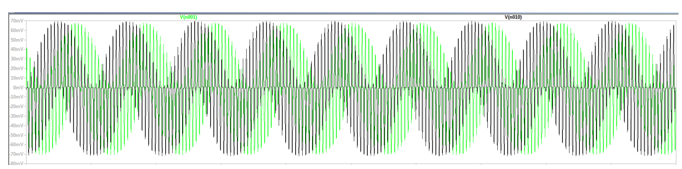

Fig. 18. This the output we get at the drain of the mixers for the above QDC circuit where the Black colored waveform is the In-phase IF and the Green one is the Quadrature-phase IF

4) Practical Circuit and Output of QDC: **Refer to Fig. 21 and Fig. 22** for the practical circuit outputs

5) Performance Summary and Comparison: **Refer to Fig. 23**

IV. Applications of the QDC

Following are the few applications of the QDC:

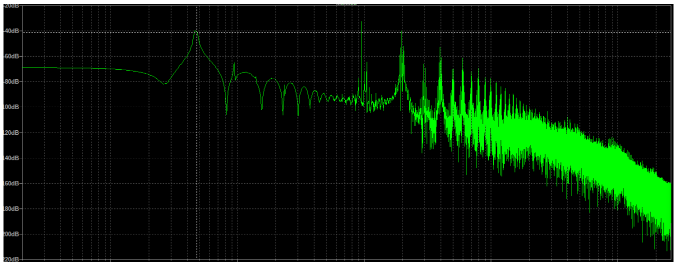

Fig. 19. This is the FFT of the waveforms obtained in Fig. 15, where the primary peak is at around 4.7kHz

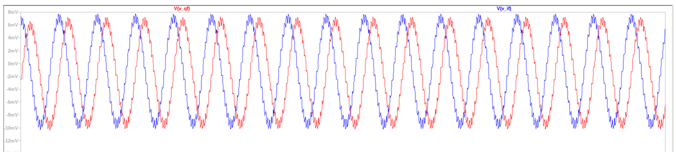

Fig. 20. This is the final output obtained after passing the IF signals via the LPF. Here, the blue waveform is for the Quadrature-Phase component and red waveform is for the In-Phase component of the input signal

1) Wireless Communication Systems: Quadrature downconverters are used in wireless communication systems, such as cellular networks, by helping to convert the received pass-band signals to a lower frequency range suitable for further processing.
2) Satellite Communication: In satellite communication systems, quadrature downconverters demodulate the signals received from satellites to baseband region and then made suitable for usage in the next circuit component. As discussed in the need for QDC, this helps in reducing noise that may get amplified at larger frequencies over large distance transmissions.
3) Software-Defined Radios (SDR): This is the application that this paper essentially aims to discuss and implement

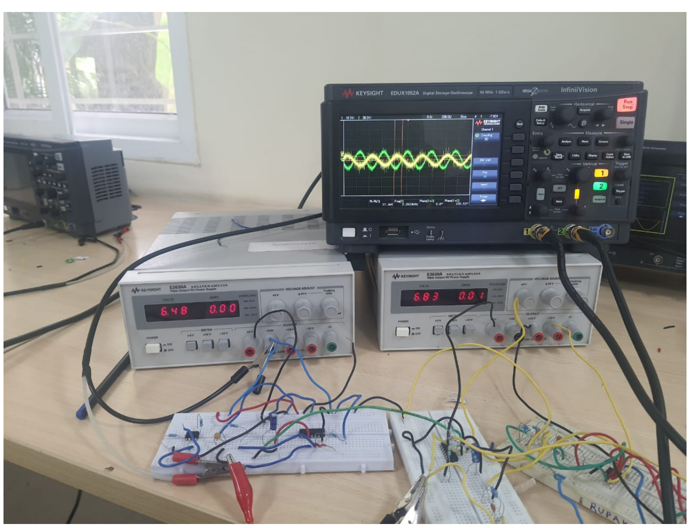

Fig. 21. Practical Circuit and the Final in-phase and Quadrature-phase Outputs of QDC

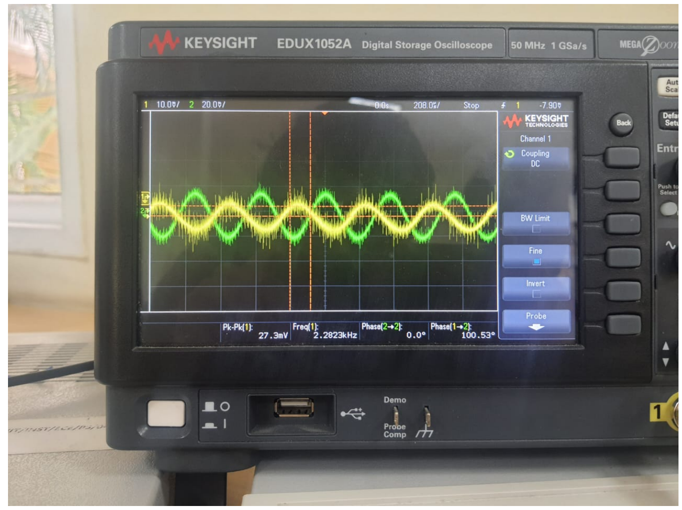

Fig. 22. Practical Output of QDC
NOTE: The green plot is the plot for the In-Phase(IF) signal and the yellow plot is the plot for the Quadrature-Phase(QF) signal

Parameters	Simulated	Measured
Oscillator Frequency (in kHz)	100	98.6
Oscillator Amplitude (I-phase) (in Vpp)	2.4	2.19
Oscillator Amplitude (Q-phase) (in V)	1	1.13
Input frequency (in kHz)	95	95
IF (in kHz)	4.7	2.7
Supply (in V)	5	5.35
VBIAS (in V)	0.7	2.45
Cc (in F)	1u	100u

Fig. 23. Table depicting performance summary and comparison of simulated and practically obtained data

- that of downconverting the RF signals to a lower range of frequency by generating an in-phase and quadrature-phase component.

4) Radar Systems: Quadrature downconverters find applications in radar systems for frequency translation and signal processing, which involves detection of objects and image processing.
5) Last but not the least, this technique is used at base-stations and transmitters for demodulating the incoming modulated signals - the idea at the core of QDC

V. Conclusion

The techniques discussed in the paper aim to appreciate a basic version of a pivotal technology used in analog communication - a Quadrature Down Converter. After providing a comprehensive explanation about the need of this oscillator in the first place and analysis in the previous sections regarding each of its building components, we can now effectively conclude with the fact that the Quadrature Down converter indeed helps in demodulating the incoming pass-band signal and extracting its in-phase and quadrature-phase components. Across decades, scientists and engineers have researched well into this field and come up with many such oscillators like Wein-Bridge Oscillator, LC Oscillator, Bubba-Oscillator, etc that have found usage in different fields of communication depending on the system and circuit requirements and specifications. The uses and applications of these concepts as realised in the previous section are quite varied and eminent in bringing about some remarkable technologies for humanity to explore. And with the changing technology, we expect and aim to see, and contribute towards extraordinary developments in this field.

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