

Quadrature Down Converter

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2023102047

2023102048

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Abstract—This paper introduces a Quadrature Down Converter (QDC) built around a quadrature oscillator, two mixers, and two low-pass filters. It outlines the design of an In-phase and Quadrature-phase for a direct conversion receiver. QDCs are integral to modern wireless receivers like Bluetooth, Wi-Fi, and WLAN, aiding in interference reduction and communication quality enhancement. The described approach likely achieves accurate signal processing, facilitating the extraction of both in-phase and quadrature-phase components efficiently. Such advancements play a significant role in elevating wireless communication standards.

I. INTRODUCTION

Frequency down converters are complex systems designed to convert high-frequency RF (Radio Frequency) signals into lower frequency IF (Intermediate Frequency) signals. At high carrier frequencies, filtering for channel selection becomes particularly challenging. This conversion process is accomplished using a "mixer," where the signal is multiplied by a sinusoid $A_0 \cos(\omega_{LO} t)$ generated by a local oscillator (LO). Multiplication in the time domain equates to convolution in the frequency domain, effectively shifting the desired channel by $\pm(\omega_{in} \pm \omega_{LO})$ due to impulses at $\pm\omega_{LO}$. Components at $\pm(\omega_{in} + \omega_{LO})$ are irrelevant and are eliminated by a low-pass filter (LPF), resulting in the signal centered at $(\omega_{in} - \omega_{LO})$. This operation is known as "down conversion."

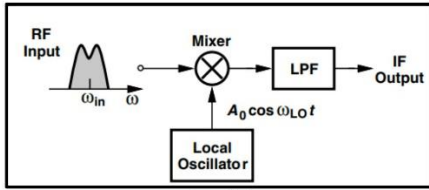


Fig 1.1

$$A \cos(\omega_{IF} t) = A \cos(\omega_{in} - \omega_{LO}) \quad (1)$$

$$A \cos(\omega_{IF} t) = A \cos(\omega_{LO} - \omega_{in}) \quad (2)$$

Equations (1) and (2) reveal that regardless of whether ω_{in} is higher or lower than ω_{LO} , the input results in the same IF. Essentially, two spectra positioned symmetrically around ω_{LO} are converted to the identical IF. This symmetry leads to the designation of the component at ω_{im} as the image of the desired signal.

$$\omega_{im} = \omega_{in} + 2\omega_{IF} = 2\omega_{LO} - \omega_{in} \quad (3)$$

There are numerous users in all standards (from police to WLAN bands) that transmit signals and produce many interferers. If one interferer happens to fall at $\omega_{im} = 2\omega_{LO} - 2\omega_{in}$, then it corrupts the desired signal after down conversion.

In various standards, ranging from police frequencies to WLAN bands, there are multiple users transmitting signals, leading to numerous sources of interference. If one of these interferers aligns with the frequency $\omega_{im} = 2\omega_{LO} - 2\omega_{in}$, it can disrupt the desired signal post down-conversion.

When an asymmetrically modulated signal is down-converted to a zero IF (Intermediate Frequency), it tends to corrupt itself unless the baseband signals are distinguished by their phases. This is where a Quadrature Down Converter comes into play as a solution. In this method, two versions of the down-converted signal are generated, each with a 90° phase difference from the other.

In quadrature down conversion, two mixers are employed, each fed with a different signal: one with a cosine wave and the other with a sine wave. Consequently, the same RF data splits into two paths to produce quadrature signals, both in baseband, denoted as BB.

The input signal $v_{in} = A_1 \cos(\omega_{in} t)$ undergoes mixing with $v_{OSCI} = A_2 \cos(\omega_{OSC} t)$ and $v_{OSCQ} = A_2 \sin(\omega_{OSC} t)$ to yield in-phase (v_{IFI}) and quadrature-phase (v_{IFQ}) intermediate frequency (IF) signals, respectively. These in-phase and quadrature-phase signals maintain a phase difference of 90° . It's worth noting that the mixing of two signals is equivalent to their multiplication.

$$v_{IFI} = v_{in} \times v_{OSCI} = \frac{A_1 A_2}{2} (\cos(\omega_{in} t - \omega_{OSC} t) + \cos(\omega_{in} t + \omega_{OSC} t)) \quad (4)$$

$$v_{IFQ} = v_{in} \times v_{OSCQ} = \frac{A_1 A_2}{2} (\sin(\omega_{in} t + \omega_{OSC} t) - \sin(\omega_{in} t - \omega_{OSC} t)) \quad (5)$$

The mixed signal is fed to a low pass filter to pass only the IF signals with frequency $\omega_{IF} = (\omega_{in} - \omega_{OSC})$, which can be a sufficiently low value for a sufficiently high value of ω_{in} and ω_{OSC} . Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

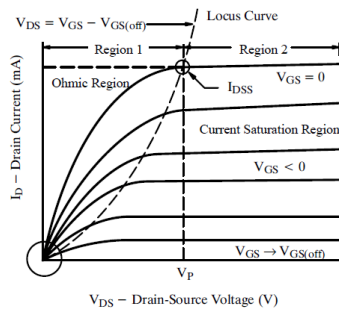
SWITCH (MIXER)

To achieve an ideal switch, certain conditions need to be met. Firstly, the duty cycle of the switch should ideally be around 50%. Additionally, the internal resistance of the switch should be minimized, ideally approaching zero. These requirements can often be fulfilled by employing a simple MOSFET setup. In this configuration, the oscillator signal is directed to the Gate of the MOSFET, while the input is fed at the source. Subsequently, the intermediate frequency output can be extracted from the drain end of the MOSFET.

A. Achieving very low Internal Resistance

A MOSFET acts as a linear resistor when it is in Linear or Triode region. We can utilize it to make a Switch. Drain Current through the MOSFET in Linear Region can be represented as in Equation below. Plot of the parabola for different values of V_{GS} is given below.

$$I_D = \mu_N C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$



If in upper equation we have $V_{DS} \ll 2(V_{GS} - V_{TH})$, we would get equation written below. This region is called as Deep Triode Region.

$$I_D = \mu_N C_{ox} \frac{W}{L} [(V_{GS} - V_{TH}) V_{DS}]$$

This means that the Drain Current is a linear function of V_{DS} . For small V_{DS} , each parabola can be approximated by a straight line. The linear relationship implies that the path from the source to drain can be represented by a linear resistor with resistance as given in Equation

$$R_{on} = \frac{1}{\mu_N C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

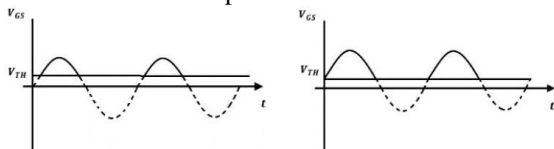
A MOSFET can therefore operate as a resistor value is controlled by the overdrive voltage when it is in Deep Triode Region.

To make the Switch Ideal, we must make this resistance very low

The Technological parameters like μ_N , C_{ox} , V_{TH} are not in our hand. So, the only way this can be done is by increasing the Aspect Ratio W/L .

B. Achieving 50% Duty Cycle

This would require you to Bias your Gate terminal at the Threshold Voltage. When Gate-Source Voltage, V_{GS} , is greater than the Threshold Voltage, V_{TH} , then the nMOS is in Linear Mode and thus conducting and when it is less it won't conduct. Thus, to get 50% Duty Cycle, V_G , i.e., V_{osc} should operate across V_{TH} .



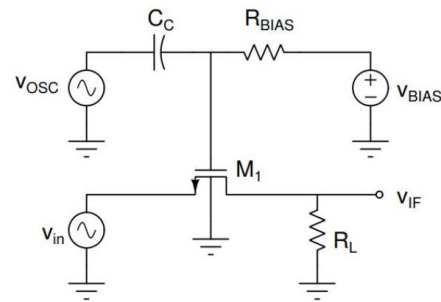
The challenge in biasing the Gate terminal arises from the inability to directly connect both AC and DC sources. This is because, when an AC signal flows, it naturally seeks a path with very low impedance connected to Ground, especially considering the very low internal resistance of an Ideal Source. However, the Gate terminal typically presents a high impedance. Consequently, the entirety of the AC current

would divert through the DC source, as it naturally follows the path of least impedance.

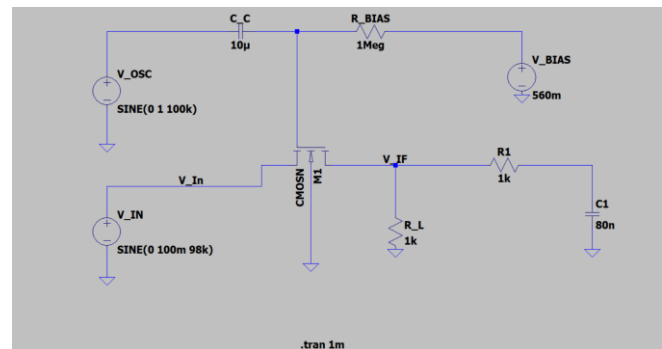
Similar discussion follows for the DC Source as well. So, unlike giving Input from the Wave Generator where we can simply specify the Offset, we need to adopt some other way to Bias the Gate terminal in real circuits.

We use a resistor, R_{BIAS} and a capacitor, C_{BIAS} for this. To prevent the flow of DC current to the AC source we can add a Capacitor, C_{BIAS} , next to the AC source. This will isolate the AC and DC sources. Thus, preventing the flow of DC current flowing through the AC source. Any small value capacitance can be chosen. We chose $C_{BIAS} = 10 \mu F$. To prevent the flow of AC Current to the DC Source we can add a Resistor, R_{BIAS} , of very high resistance next to the DC source to increase the impedance. Thus, preventing the AC current to flow through the DC source. Any high value for the resistance can be chosen. We chose $R_{BIAS} = 1 M\Omega$.

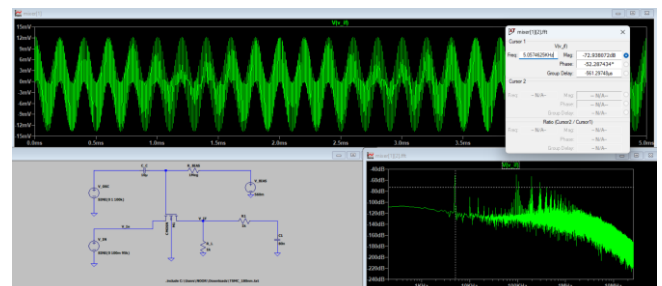
C. Circuit



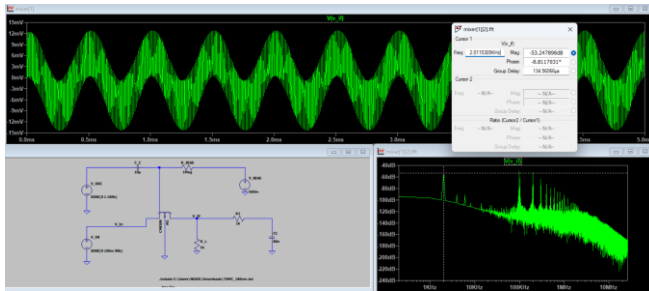
D. LT SPICE SIMULATIONS



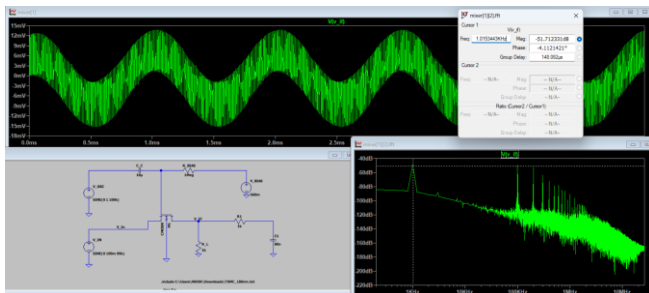
1) AT f=95 Hz



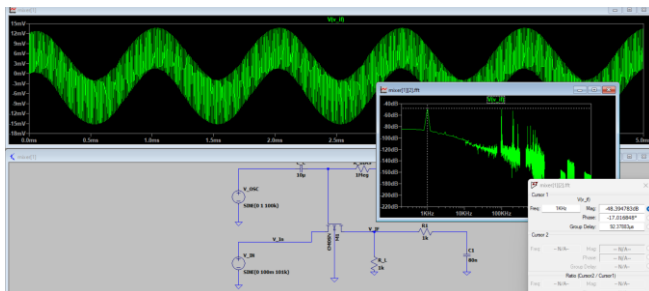
2) AT $f=98$ Hz



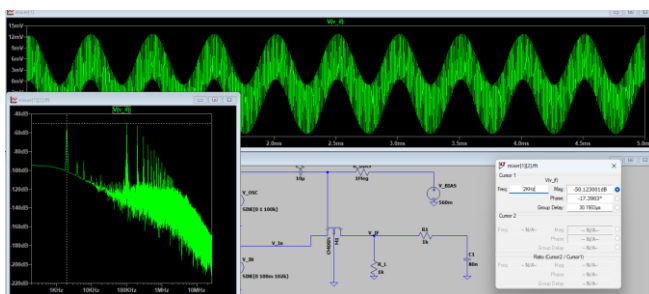
3) AT $f=99$ Hz



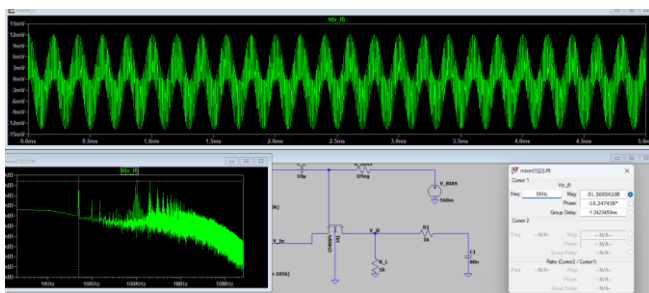
4) AT $f=101$ Hz



5) AT $f=102$ Hz



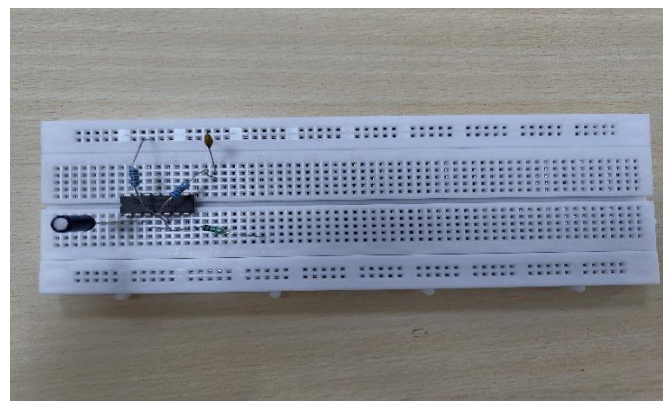
6) AT $f=105$ Hz



DSO OBSERVATION:



HARDWARE CIRCUIT:



QUADRATURE OSCILLATOR

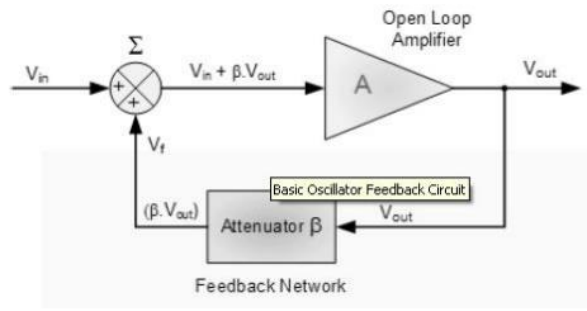
Oscillators are fundamental in generating consistent-frequency sinusoidal waves with stable amplitudes. These circuits are versatile, producing various periodic waveforms such as square, triangular, sawtooth, and sinusoidal. They are broadly classified into two categories: relaxation and sinusoidal oscillators. Relaxation oscillators yield non-sinusoidal waveforms like triangular and sawtooth. Sinusoidal oscillators, like the quadrature type, specifically generate sinusoidal signals. Quadrature generators produce two sinusoids with identical frequency and amplitude but with differing phase angles. Notably, a rectangular quadrature signal exhibits a distinct 90° phase shift between the two components.

A. How to make an oscillator

Oscillators do not need an externally applied input signal, instead, they use some fraction of the output signal created by the feedback network as the input signal.

- Oscillation results when the feedback system is not able to find a stable steady-state because its transfer function cannot be satisfied. The system becomes unstable when $1 + A\beta = 0$ or $A\beta = -1$.

- Moreover, the magnitude of loop gain must be unity with a corresponding phase shift of 180° degrees.



As the phase shift approaches 180° and $|A\beta| \rightarrow 1$, the output voltage of the now unstable system tends to infinity but, it is limited to finite values by an energy-limited power supply. The value of A changes and forces $A\beta$ away from the singularity as the output voltage approaches either of the power rail. Thus, the trajectory towards an infinite voltage slows and eventually halts. The system stays linear and reverses direction, heading to the opposite power rail. This produces a sine wave oscillator.

When using large feedback resistors, care must be taken, as they interact with the input capacitance of the op-amp to create poles with negative feedback and, both poles and zeros with positive feedback. Large resistor values can move these poles and zeros into the neighborhood of the oscillation frequency and affect the phase shift. Furthermore, op-amp's slew rate limitation must be taken into consideration.

The slew rate must be greater than $2\pi V_P f_o$, where V_P is the peak voltage and f_o is the oscillation frequency. Otherwise,

$$\Phi = \tan^{-1}(-wRc) - \tan^{-1}\left(\frac{1}{wrc}\right) + \frac{\pi}{2}$$

$$\text{Frequency} = 1/2\pi RC$$

$$\omega = 1/RC$$

$$\omega = 2\pi f$$

distortion of the output signal occurs.

C. How does a Quadrature Oscillator work

In a quadrature oscillator, the original sine wave is 180° phase shifted. This is because the double integral of a sine wave is a negative sine wave of same frequency and phase. The phase of the second integrator is then inverted and applied as positive feedback to induce oscillation.

The loop gain is calculated from the following equation:

$$A\beta = A \left(\frac{1}{R_1 C_1 s} \right) \left[\frac{R_3 C_3 s + 1}{R_3 C_3 s (R_2 C_2 s + 1)} \right]$$

When $R_1 C_1 = R_2 C_2 = R_3 C_3$ the equation becomes,

$$A\beta = A \left(\frac{1}{RCs} \right)^2$$

When $\omega = 1/RC$, the equation reduces to $1 \angle -180^\circ$, so oscillation occurs at $\omega = 2\pi f = 1/RC$. Adjusting the gain can increase the amplitudes. But as a trade-off, we would have reduced bandwidth.

D. Requirements for the Quadrature Oscillator

Amplitude of cos and sine wave = 1Vpp

Frequency = 100kHz

Phase difference = 90°

Phase Difference is calculated as follows from the above circuit.

Amplitude is very low. It is amplified by using amplifier circuits.

$$\text{Gain} = 1 + R_2/R_1$$

In accordance with the design requirements, the following values have been taken for the quadrature oscillator:

(a) $R_1 = R_2 = R_3 = 8.2k\Omega$

(b) $R_4 = R_7 = 1k\Omega$

(c) $R_5 = R_6 = 12k\Omega$

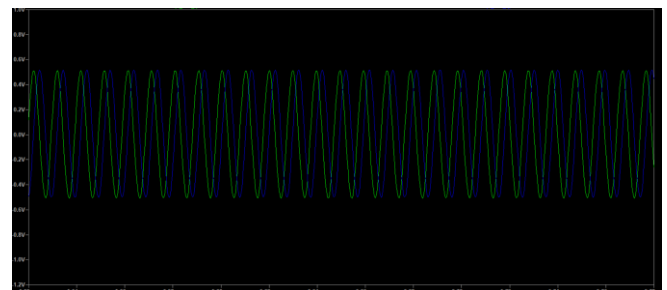
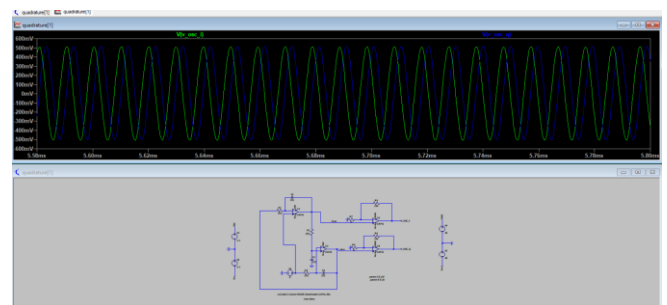
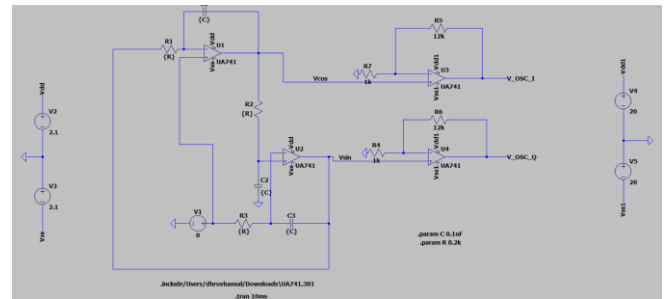
(d) $C_1 = C_2 = C_3 = 0.1nF$

(e) $V_{ss}(\text{oscillator}) = -2.1V$, $V_{DD}(\text{oscillator}) = 2.1V$

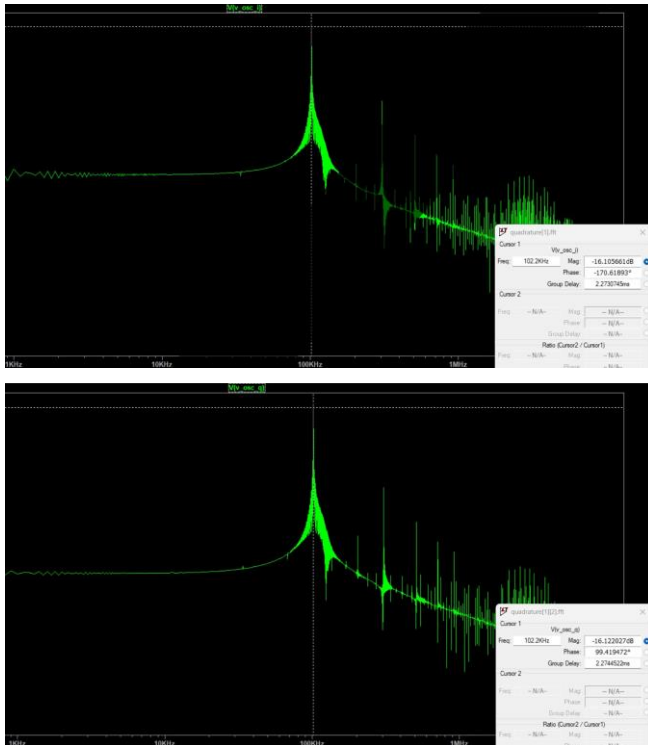
(f) $V_{ss}(\text{amplifier}) = -20V$, $V_{DD}(\text{amplifier}) = 20V$

(g) Op-Amp UA 741

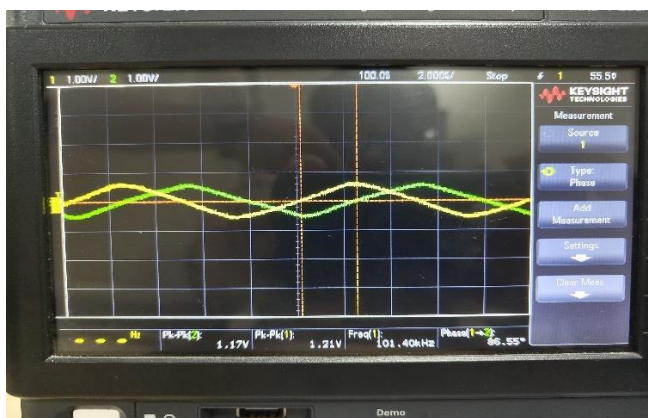
E. LT Spice observations



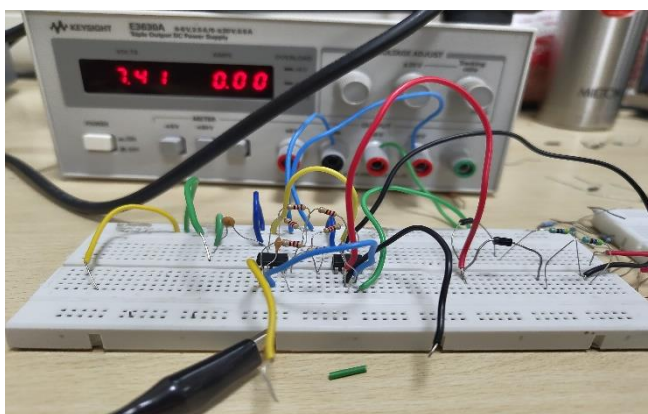
FFT OF SINE AND COSINE WAVES



DSO OBSERVATION



HARDWARE IMAGE

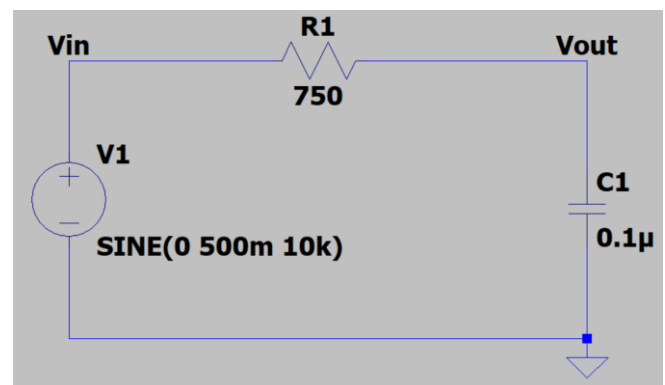


LOW PASS FILTER

A Low Pass Filter serves to adjust, reshape, or eliminate unwanted high frequencies from an electrical signal, allowing only desired signals to pass through. Essentially, it permits low-frequency signals while obstructing high-frequency ones. Signals below a designated frequency, known as the cut-off frequency, are allowed to pass, while anything beyond this frequency is attenuated or blocked by the filter. In applications with frequencies up to 100kHz, passive filters are commonly crafted using simple RC (Resistor-Capacitor) networks. Conversely, for higher frequency applications above 100kHz, RLC (Resistor-Inductor-Capacitor) components are often utilized. Passive filters are constructed from components like resistors, capacitors, and inductors, lacking amplifying elements such as transistors or op-amps, thus they provide no signal gain, resulting in an output level always lower than the input.

RC Low Pass Filter: A passive low pass filter is made of a resistor connected in series with a capacitor and the output is taken across the capacitor. This type of filter is known generally as a “first order filter” because it has only one reactive component in the circuit i.e., the capacitor

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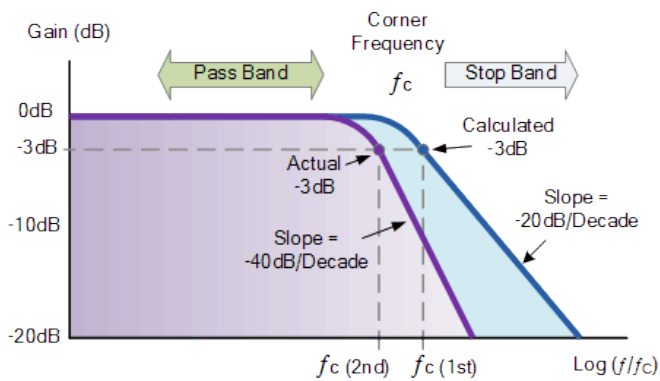
The reactance of a capacitor varies inversely with frequency, while the value of the resistor remains constant as the frequency changes. The capacitor allows a high-frequency signal and blocks low-frequency signal.

a) Frequency Response

$$V_{out} = V_{in} \times \frac{X_C}{R + X_C}$$

$$V_{out} = V_{in} \times \frac{1}{1 + j2\pi fRC}$$

$$\left| \frac{V_{out}}{V_{in}} \right| = \frac{1}{\sqrt{1 + (2\pi fRC)^2}}$$



At low frequencies the capacitive reactance, (X_C) of the capacitor is very large as compared to the resistive value of the resistor (R). So, the capacitor acts as an open circuit and the signal will appear across its terminal, which will eventually flow out as output. This can be observed from equation. However, at high frequencies, the capacitive reactance (X_C) is very less than the resistance (R) of the resistor. So, when the high-frequency signal reaches the capacitor acts as a short circuit and the output becomes zero.

b) Cut-off Frequency Cut-off frequency, also known as corner frequency, denoted by f_c is the selected frequency point where the output signal's power becomes -3dB or 70.7% of the input signal. At this frequency, the capacitive reactance X_c and resistor's resistance R become equal. The low pass filter allows frequency below the cut-off frequency and blocks any frequency higher than the cut-off frequency. Where the cut-off frequency is calculated by:

$$20 \log \left| \frac{V_{out}}{V_{in}} \right| = -3dB$$

$$20 \log \left(\frac{1}{\sqrt{1+(2\pi fRC)^2}} \right) = -3$$

$$f_c = \frac{1}{2\pi RC}$$

To design a low pass filter with -3dB cut off frequency of 2kHz, f_c is taken as 2kHz.

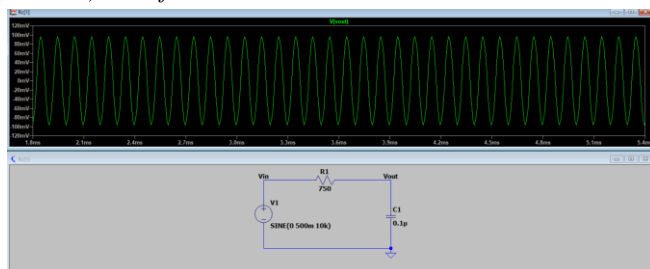
$$2 \times 10^3 = \frac{1}{2\pi RC}$$

$$RC = 75 \times 10^{-6}$$

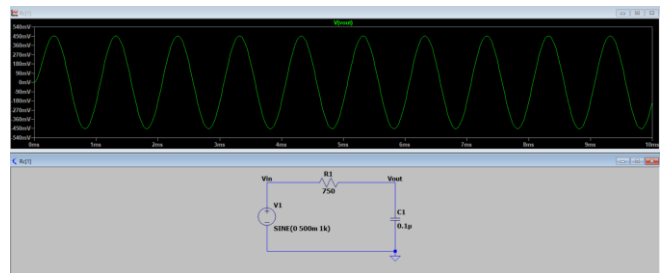
Taking $R = 750\Omega$ and $C = 0.1\mu F$

LT SPICE OBSERVATIONS:

a) FOR $f=10kHz$

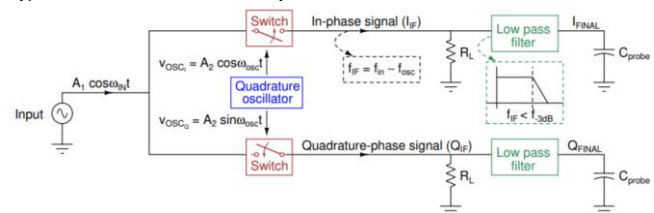


b) FOR $f=1KHz$

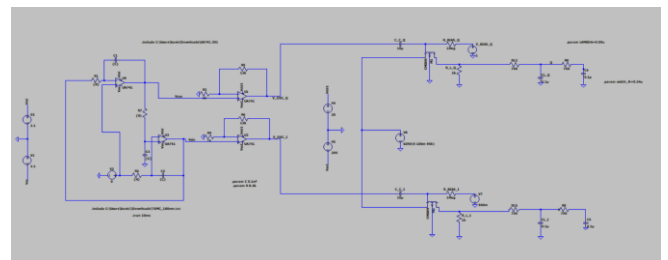


COMPLETE CIRCUIT

Connecting all the building blocks – Oscillator, Mixer and Filter, the final circuit is implemented. The final circuit will produce two waves IFI and IFQ which are the in-phase and the quadrature-phase components of the IF signal. These signals have a phase difference of 90° .

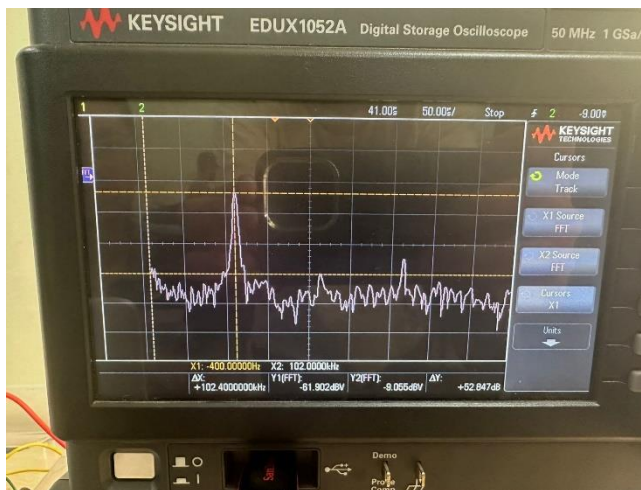


LT SPICE SIMULATIONS

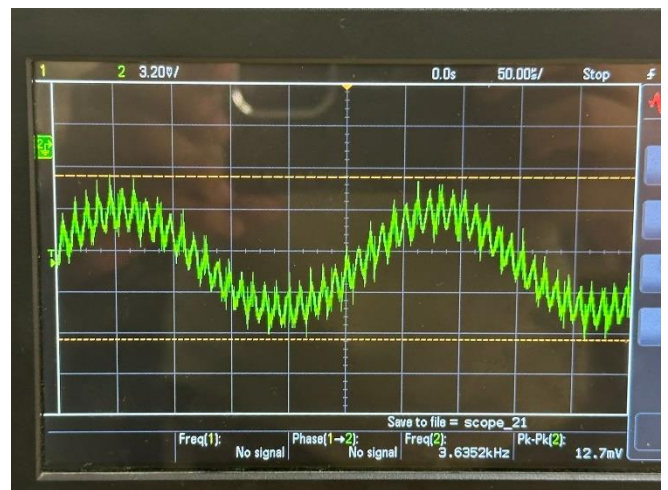


It is observed that the first peak in the FFT plot is at 2kHz. The input signal has a frequency of 98kHz, and the waves generated by the oscillator have a frequency of 100kHz. When these waves are mixed and are passed through the low pass filter, only the component of the signal with a frequency less than the cutoff frequency gets passed, i.e., the wave with frequency $f_{OSC} - f_{in}$.

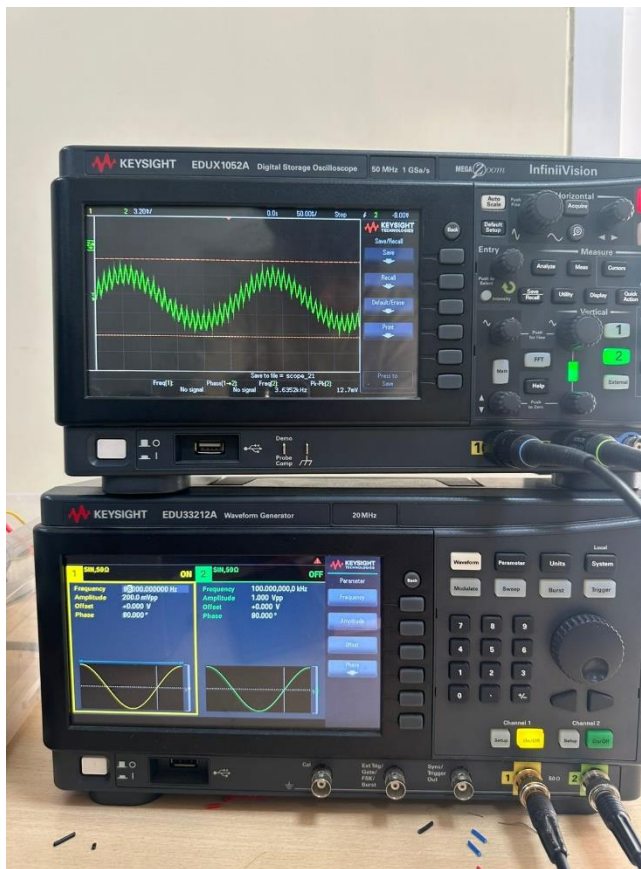
LAB OBSERVATIONS:



Final Output of Oscillator



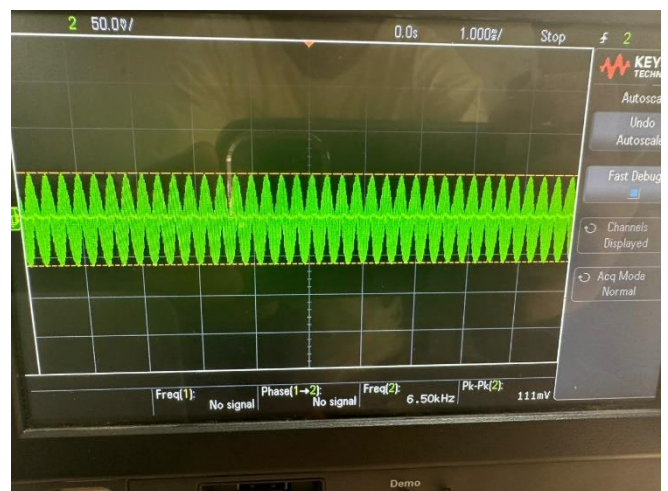
Zoomed in version



Final Output



1. quadrature output 2. final output



Mixer output

Performance Summary and Comparison

<i>Parameters</i>	<i>Simulated</i>	<i>Measured</i>
<i>Oscillator Frequency</i>	<i>100kHz</i>	<i>100.5kHz</i>
<i>Oscillator Amplitude (I-phase)</i>	<i>1V (peak to peak)</i>	<i>1.07V (peak to peak)</i>
<i>Oscillator Amplitude (Q-phase)</i>	<i>1V (peak to peak)</i>	<i>1.01V (peak to peak)</i>
<i>Input Frequency</i>	<i>98kHz</i>	<i>98kHz</i>
<i>IF</i>	<i>2kHz</i>	<i>2.3kHz</i>
<i>Supply</i>	<i>100mv</i>	<i>100mv</i>
<i>V_{BLAS}</i>	<i>560mV</i>	<i>800mV</i>
<i>C_C</i>	<i>10uF</i>	<i>10uF</i>
<i>R_{BLAS}</i>	<i>1M</i>	<i>1M</i>
<i>R₁, R₂, R₃</i>	<i>8.2kΩ</i>	<i>820Ω</i>
<i>C₁, C₂, C₃</i>	<i>0.1nF</i>	<i>1nF</i>

ACKNOWLEDGMENT

The Authors of this paper would like to thank International Institute of Information Technology, Hyderabad for the sponsored access to several scientific websites like IEEE. Thanks are given to Prof. Abhishek Srivastava for providing support and this platform to study and present ideas on this topic. The authors also give thanks to the teaching assistants

of the Analog Electronic Circuits course of the Institute for their help and useful comments on the paper.

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CONTRIBUTION

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