Quadrature Down Converter

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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 A0cos(ωLOt) generated by a local oscillator (LO). Multiplication in the time domain equates to convolution in the frequency domain, effectively shifting the desired channel by ±(ωin ± ωLO) due to impulses at ±ωLO. Components at ±(ωin + ωLO) are irrelevant and are eliminated by a low-pass filter (LPF), resulting in the signal centered at (ωin - ωLO). This operation is known as "down conversion."

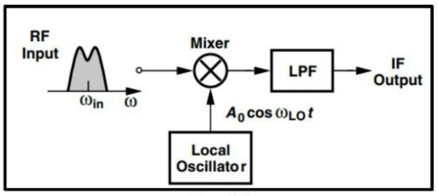


Fig 1.1

$$Acos(\omega_{IF}t) = Acos(\omega_{in} - \omega_{LO}) \quad (1)$$
$$Acos(\omega_{IF}t) = Acos(\omega_{LO} - \omega_{in}) \quad (2)$$

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

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

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 ωim = 2ωLO - 2ωin, 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 ωim = 2ωLO - 2ωin , 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 vin = A1cos (ωin$t$) undergoes mixing with $vOSCI$ = A2cos (ω$OSCt$) and $vOSCQ$ = A2sin (ω$OSCt$) to yield in-phase ($vIFI$) and quadrature-phase ($vIFQ$) 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.

$$v_{IF_I} = v_{in} \times v_{OSC_I} = \frac{A_1A_2}{2}(\cos(\omega_{\text{in}}t - \omega_{\text{osc}}t) + \cos(\omega_{\text{in}}t + \omega_{\text{osc}}t)) \quad (4)$$

$$v_{IF_Q} = v_{in} \times v_{OSC_Q} = \frac{A_1A_2}{2}(\sin(\omega_{\text{in}}t + \omega_{\text{osc}}t) - \sin(\omega_{\text{in}}t - \omega_{\text{osc}}t)) \quad (5)$$

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

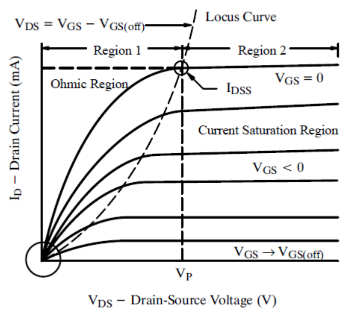
SWITCH (MIXER)

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 VGS 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 $VDS \ll 2(VGS - VTH)$, 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 VDS . For small VDS , 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

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

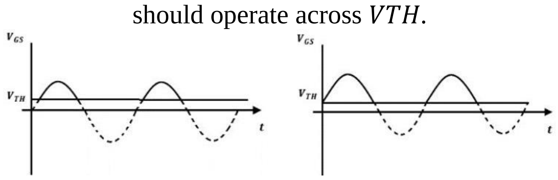
A MOSFET can therefore operate as a resistor value is controlled by the overdrive voltage when it is in Deep Triode Region.

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

The Technological parameters like μN, Cox, VTH 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, VGS , is greater than the Threshold Voltage, VTH, 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, VG, i.e., $Vosc$ should operate across VTH.

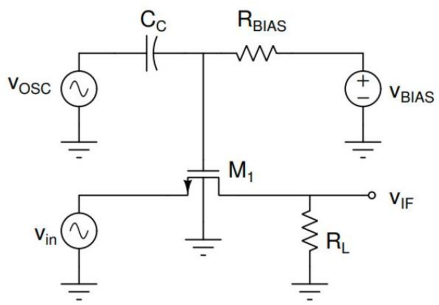


The challenge in biasing the Gate terminal arises from the inability to directly connect both AC and DC sources. This is because, when an AC signal flows, it naturally seeks a path with very low impedance connected to Ground, especially considering the very low internal resistance of an Ideal Source.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

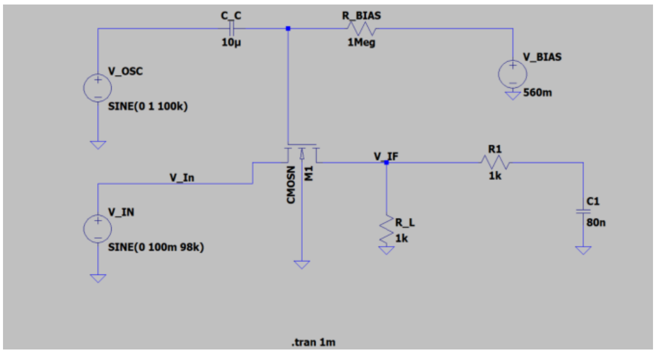
Similar discussion follows for the DC Source as well. So, unlike giving Input from the Wave Generator where we can simply specify the Offset, we need to adopt some other way to Bias the Gate terminal in real circuits.

We use a resistor, $RBIAS$ and a capacitor, $CBIAS$ for this. To prevent the flow of DC current to the AC source we can add a Capacitor, $CBIAS$, 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 $CBIAS = 10\ \mu F$. To prevent the flow of AC Current to the DC Source we can add a Resistor, $RBIAS$, 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 $RBIAS = 1M\Omega$.

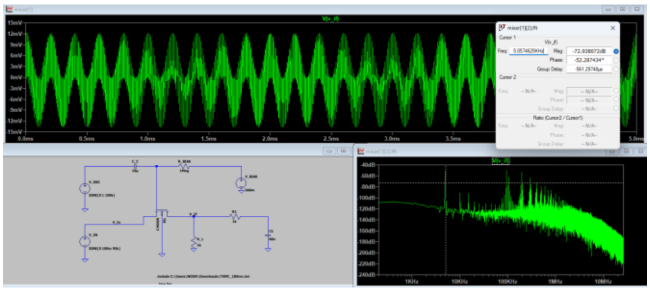
C. *Circuit*



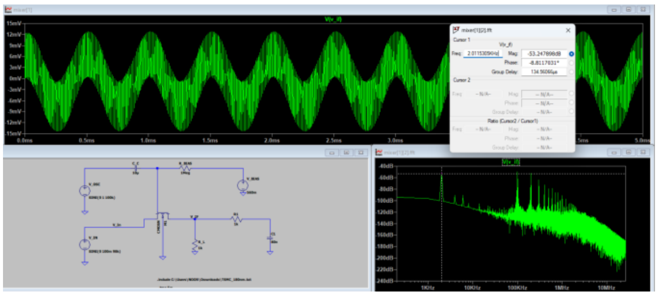
D. *LT SPICE SIMULATIONS*



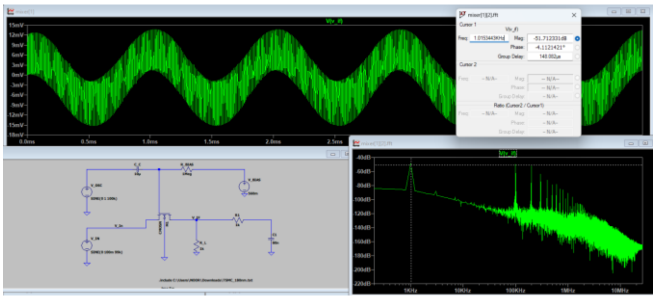
1)AT f=95 Hz



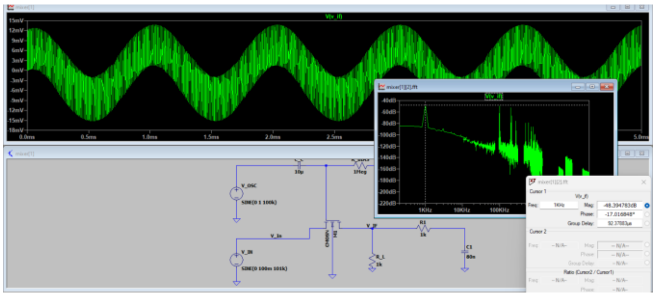
2) AT f=98 Hz



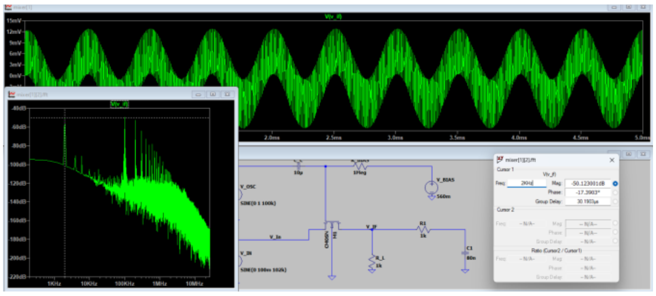
3) AT f=99Hz



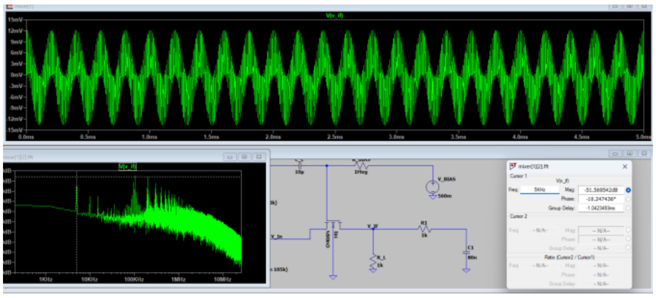
4) AT f=101 Hz



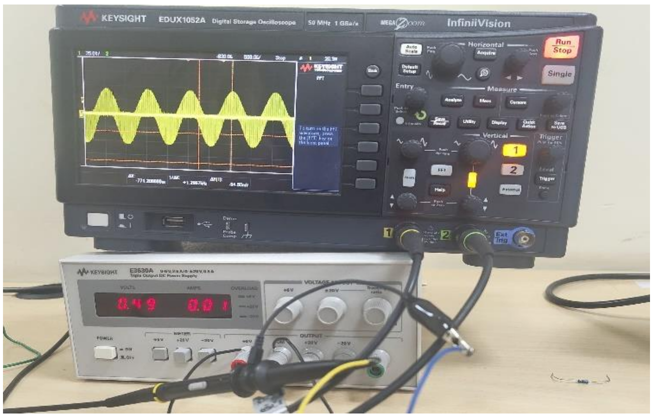
5) AT f=102 Hz



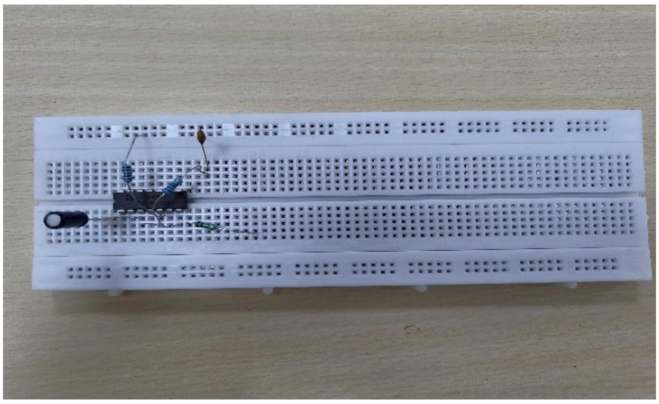
6) AT f=105 Hz



DSO OBSERVATION:



HARDWARE CIRCUIT:



QUADRATURE OSCILLATOR

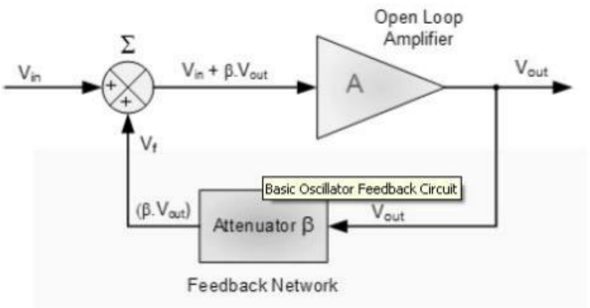
Oscillators are fundamental in generating consistent-frequency sinusoidal waves with stable amplitudes. These circuits are versatile, producing various periodic waveforms such as square, triangular, sawtooth, and sinusoidal. They are broadly classified into two categories: relaxation and sinusoidal oscillators. 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 1800 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 Aβ 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 $2\pi VPfo$, where VP is the peak voltage and fo is the oscillation frequency. Otherwise,

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

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 1800 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:

$$A\beta = A\left(\frac{1}{R_1C_1s}\right)\left[\frac{R_3C_3s+1}{R_3C_3s(R_2C_2s+1)}\right]$$

When $R_1C_1 = R_2C_2 = R_3C_3$ the equation becomes,

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

When $\omega = 1/RC$, the equation reduces to $1\angle{-180}$, 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

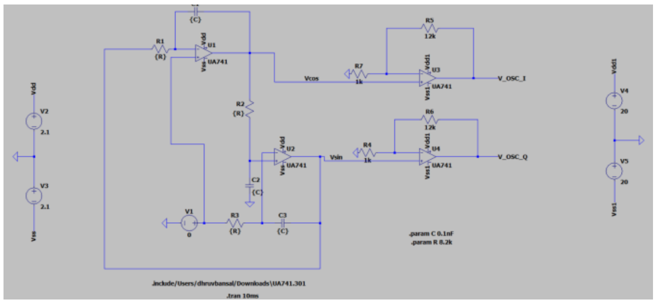
Amplitude of cos and sine wave = 1Vpp
Frequency = 100kHz
Phase difference = 90^0

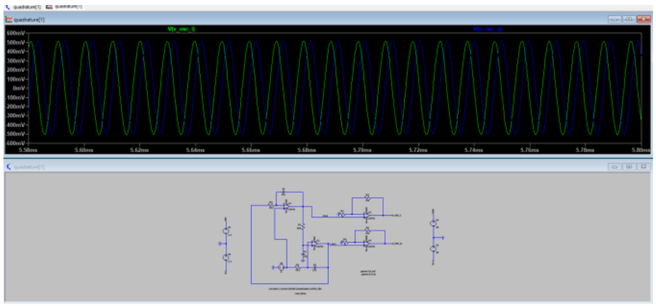
Phase Difference is calculated as follows from the above circuit.

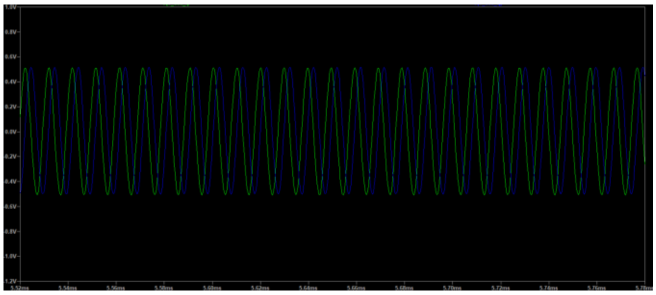
Amplitude is very low. It is amplified by using amplifier circuits.
Gain = $1+R_2/R_1$

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} (oscillator) = -2.1V , V_{DD} (oscillator) = 2.1V
(f) V_{ss} (amplifier) = -20V , V_{DD} (amplifier) = 20V
(g) Op-Amp UA 741

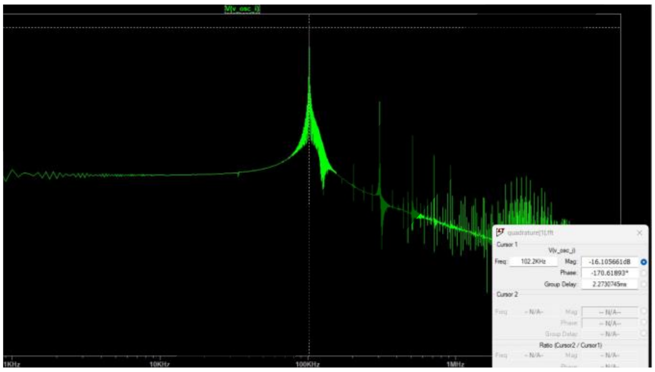
E. LT Spice observations

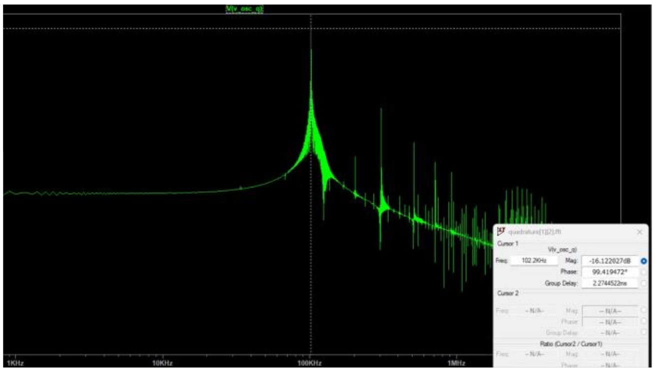






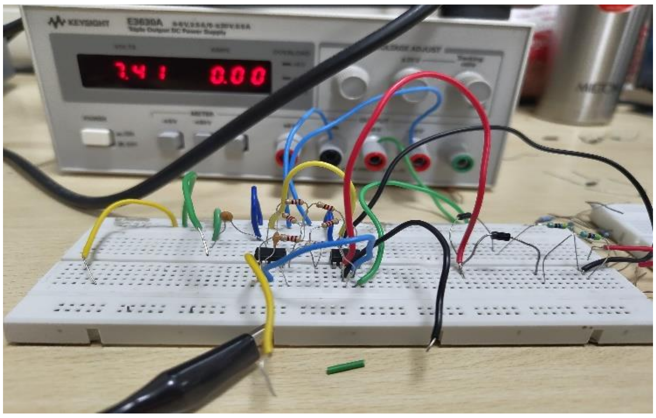
FFT OF SINE AND COSINE WAVES





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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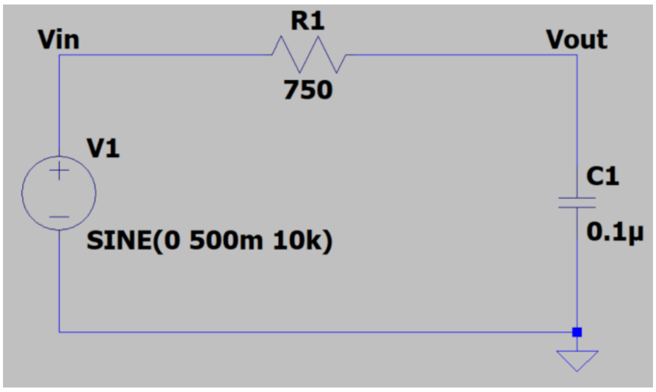


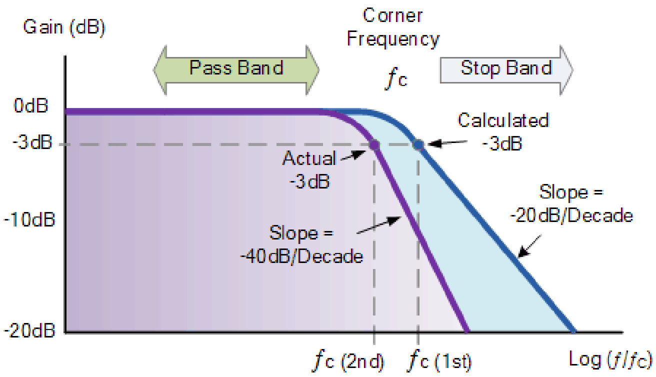
The reactance of a capacitor varies inversely with frequency, while the value of the resistor remains constant as the frequency changes. The capacitor allows a high-frequency signal and blocks low-frequency signal.

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, (XC) 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 (XC) 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 fc 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 Xc 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:

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

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

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

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

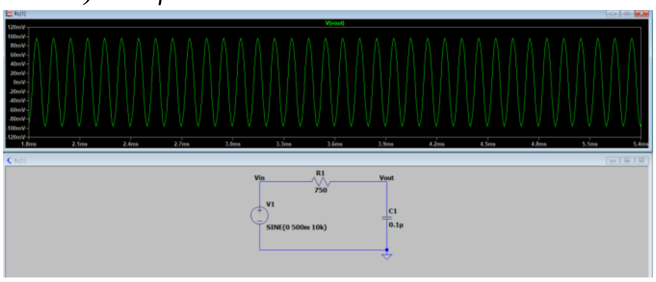
$$2 \times 10^3 = \frac{1}{2\pi RC}$$

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

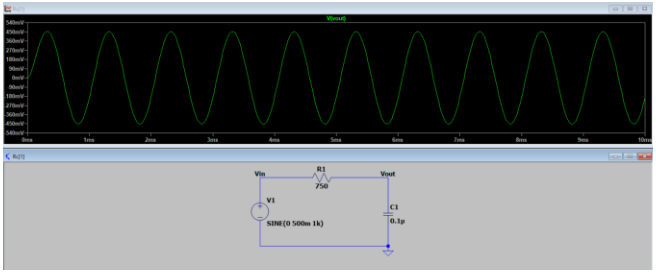
$$Taking\ R = 750\Omega\ and\ C = 0.1uF$$

LT SPICE OBSERVATIONS:

a) FOR f=10kHz

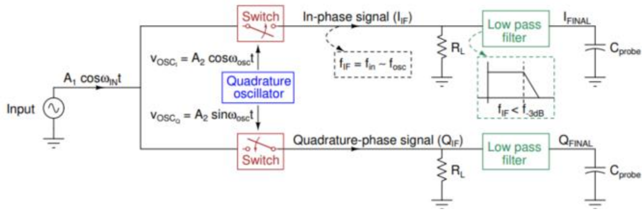


b) FOR f=1KHz

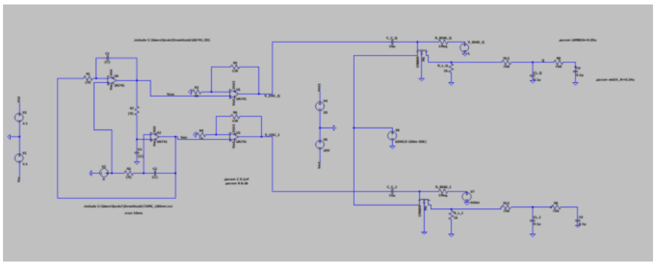


COMPLETE CIRCUIT

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°.

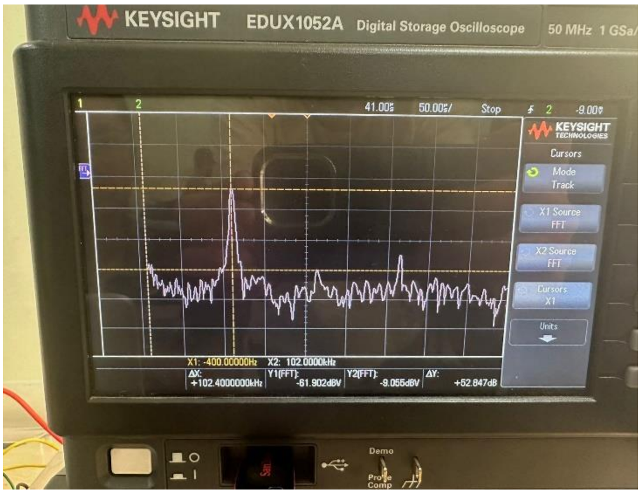


LT SPICE SIMULATIONS

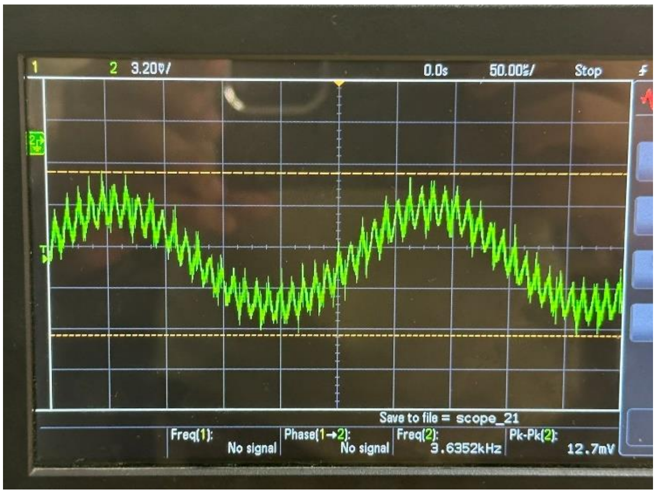


It is observed that the first peak in the FFT plot is at 2kHz. The input signal has a frequency of 98kHz, and the waves generated by the oscillator have a frequency of 100kHz. When these waves are mixed and are passed through the low pass filter, only the component of the signal with a frequency less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

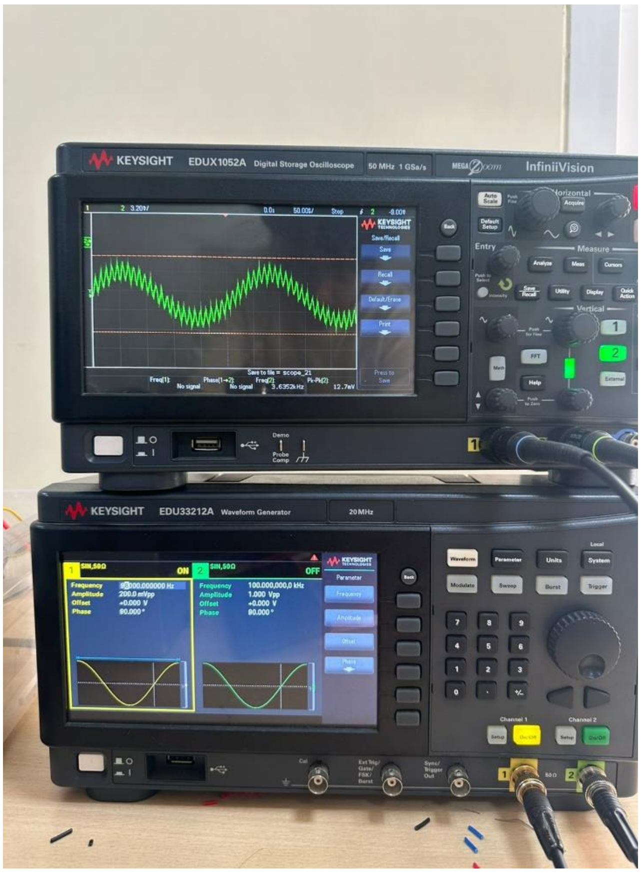
LAB OBSERVATIONS:



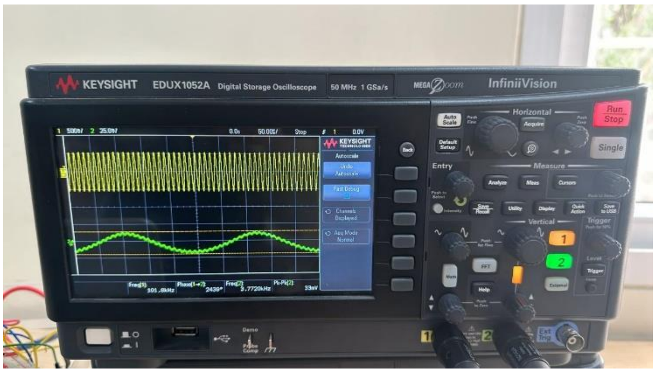
Final Output of Oscillator



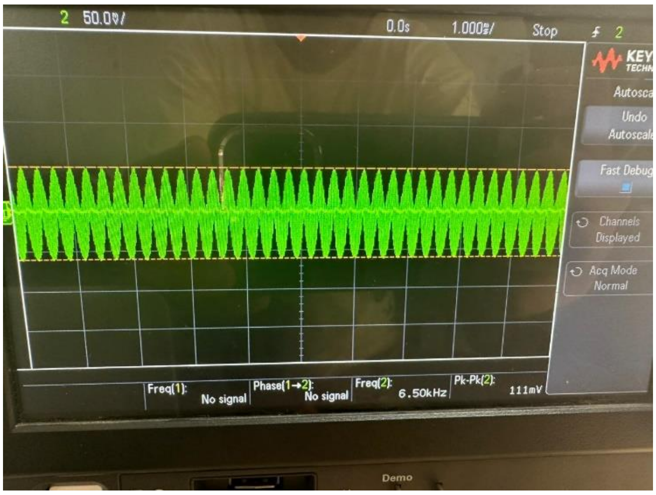
Zoomed in version



Final Output



1. quadrature output 2. final output



Mixer output

Performance Summary and Comparison

Parameters	Simulated	Measured
Oscillator Frequency	100kHz	100.5kHz
Oscillator Amplitude (I-phase)	1V (peak to peak)	1.07V (peak to peak)
Oscillator Amplitude (Q-phase)	1V (peak to peak)	1.01V (peak to peak)
Input Frequency	98kHz	98kHz
IF	2kHz	2.3kHz
Supply	100mv	100mv
V_{BIAS}	560mV	800mV
C_C	10uF	10uF
R_{BIAS}	1M	1M
R_1, R_2, R_3	8.2kΩ	820Ω
C_1, C_2, C_3	0.1nF	1nF

ACKNOWLEDGMENT

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CONTRIBUTION

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[3]Project Report-Dataarnoor & Dhruv