Quadrature Down Converter

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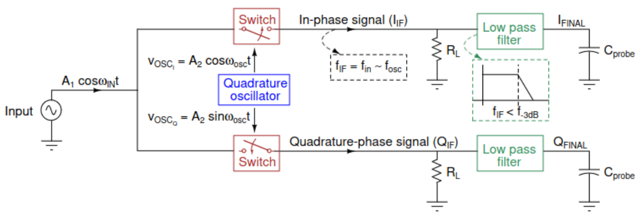
***Abstract*—The Quadrature Down-Converter is used in modern communication methods. It is used in wireless receivers such as WLAN, Wi-Fi, Bluetooth. The down converter converts a high frequency signal to a lower intermediate frequency signal and improves the quality of communication by making sure that noise in the output is minimum. The below analog down converter uses a Quadrature Oscillator, mixer and a low-pass filter.**

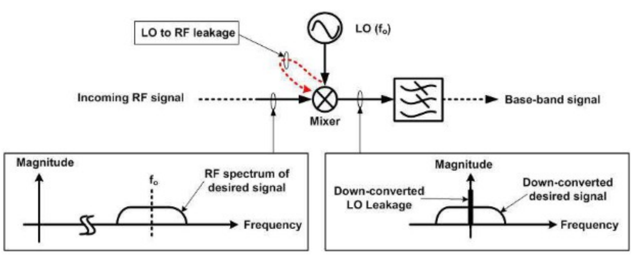
I. Introduction

Frequency Down converter convert a high-frequency RF (Radio frequency) signal to a lower frequency IF (Intermediate Frequency) signal. The local oscillator (LO) generates a sinusoid which is multiplied to the required signal and shifts it accordingly. For this design, we don't need the sum of the frequencies, so we use a low-pass filter to get rid of these high frequencies and get our desired difference of frequencies.



The above figure represents the down converter. It comprises of three main components:

- The quadrature oscillator
- The mixer
- The low-pass filter



The quadrature oscillator generates a pair of sinusoidal signals with the desired frequency. The frequency is typically determined by the specifications of the down converter and the application requirements. The quadrature oscillator generates two signals that have a precise 90-degree phase separation. The in-phase (I) signal and the quadrature (Q) signals, are used as the LO signals in the down converter.

Mixers are used to translate the frequency of the incoming RF signal to the intermediate frequency (IF) of interest. Frequency translation is typically performed by multiplying the incoming RF signal by the local oscillator (LO) signal in the time domain. The multiplication of the RF signal and the LO signal is typically done by exploiting the nonlinear (NL) characteristics of a circuit. The result is the generation of two output signals: the sum and difference frequencies. The sum frequency is typically filtered out using an LPF of desired RC values, while the difference frequency corresponds to the desired down converted signal.

II. Subcomponents of the circuit

A. QUADRATURE OSCILLATOR

A quadrature oscillator is an electronic oscillator that generates two sinusoidal signals with a phase difference of 90 degrees between them. The two output signals are referred to as **"in phase (I)"** and **"quadrature (Q)"** signals.

The fundamental working principle of a quadrature oscillator is based on feedback resonance, to generate the required sinusoidal signals. A typical implementation of a quadrature oscillator involves an amplifier (here: operational amplifier UA741) and a feedback network. The feedback network consists reactive elements such as capacitors and inductors that provide the necessary phase shift and feedback to sustain oscillation in the circuit.

The Quadrature Oscillator works in the following way:

- Amplification Stage: The amplifiers in the circuit amplify the signals to provide the required gain to maintain oscillation.

- Phase Shift and Feedback: The feedback network introduces a phase shift of 90 degrees in one of the paths. This phase shift is typically achieved using reactive components such as capacitors and resistors (RC-based design.). The output of the amplifier is fed back to the input through the phase shifting network. This feedback helps sustain the oscillation by providing positive feedback.
- The components in the circuit are selected in such a way that the circuit operates at a resonant frequency. This resonance condition ensures that the circuit amplifies the desired frequency components and supresses others.

Here, we call our in phase (I) signal as v_{oscI} and our quadrature (Q) signal as v_{oscQ}. Our goal is to produce these phase shifted signals with a frequency of 100kHz and an amplitude of $1V_{pp}$.

The topology we used for the circuit:

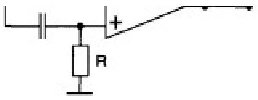


Fig. 1. First-order allpass filter.

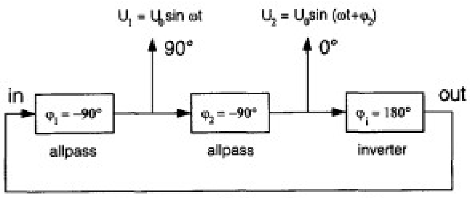
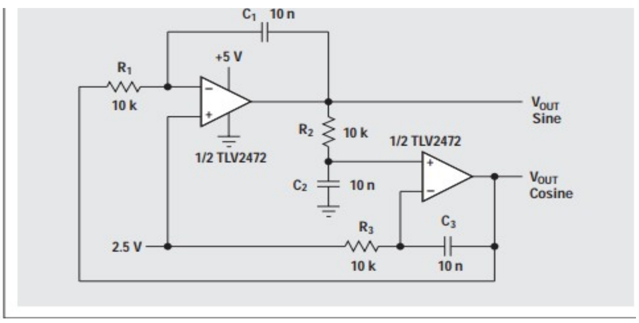
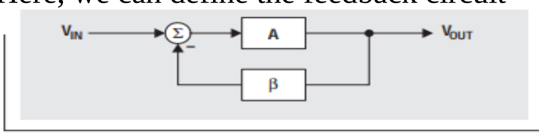


Fig. 2. Block-diagram of the quadrature oscillator.



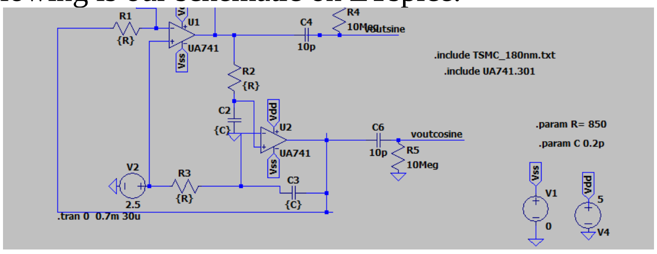
Here, we can define the feedback circuit



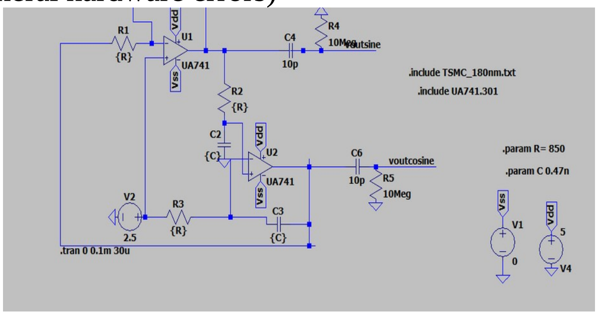
Here; we can formulate that:

$$\frac{V_{out}}{V_{in}} = \frac{A}{1 + A\beta}$$

We have understood the fundamental workings and the topology of the quadrature oscillator. The following is our schematic on LTspice.



This is the circuit we made with hardware componenents (slight change in values due to general hardware errors)

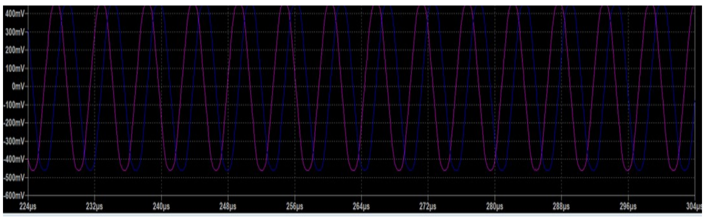


We initially used the formula

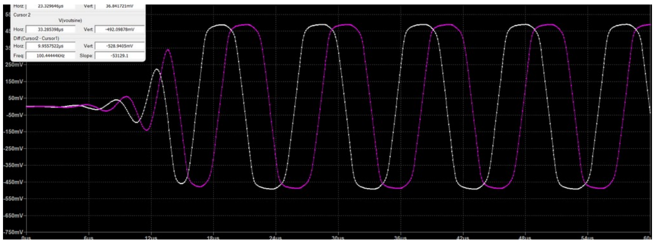
$$\omega = \frac{1}{RC}$$

To find the values of R and C. But, the frequency of the output wasn't upto requirement due to physical constraints of the circuit. Hence, through the process of trial and error, and with reference to the above mentioned formula, we came up with the required values.

The following is the corresponding transient plots of the two sinusoidal waves with a phase difference.

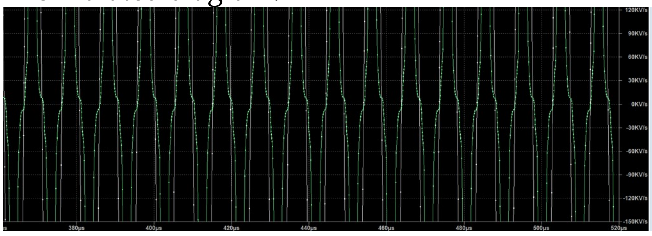


The above is the wave we get with the hardware values. We get the simulated frequency as higher than required, but due to non ideal conditions in practical scenarios, we get the required frequency in the lab.



To check for phase difference, we can use the intrinsic property of a sinusoidal wave, where differentiating a sin/cos wave leads to a 90 degree phase shift.

In simulated diagram:

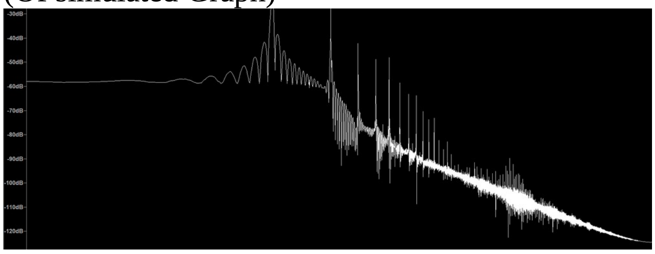


As you can see here, the graph of Vout(sine) and the graph of d(Voutcosine) overlap. This overlap isn’t perfect, since our sine and cosine generated waves aren’t perfect. Hence, we can say that the two generated waves have a phase difference of 90 degrees.

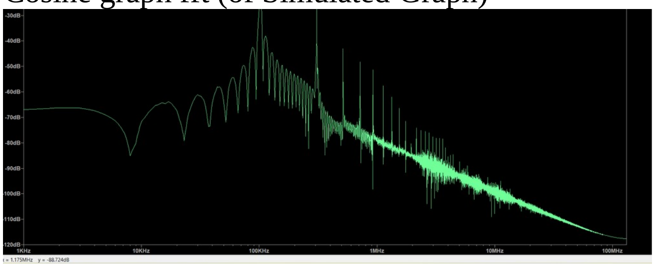
Now taking the fast fourier transformation of each graph individually:

Sine graph fft:

(Of simulated Graph)

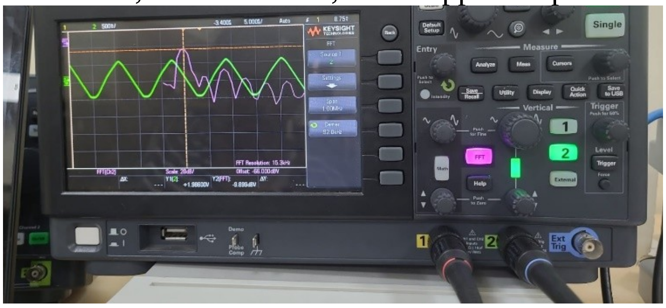


Cosine graph fft (of Simulated Graph)

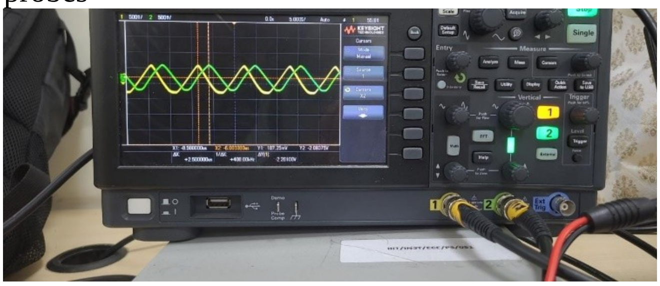


Now, we connect the above circuit on a breadboard.

Sine wave, around 92kHz, 925mVpp from probes

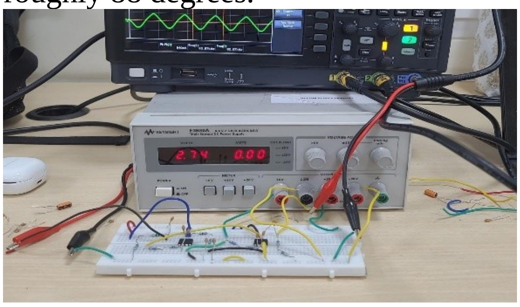


Cosine wave, Around 90kHz, 831mVppfrom probes



Phase shift calculations;

Variation in time axis between peak of sine and cosine wave = 2.65 us. Using 92kHz, we get our final phase shift as 87.768 degrees, which is roughly 88 degrees.



Our circuit with the output.

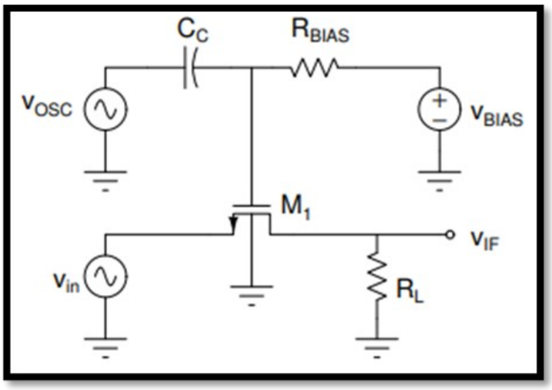
B. *SWITCH MIXER*

The switch mixer circuit is used to multiply two signals which are given to different terminals of the MOSFET. The objective of multiplying the signal is to extract the initial input wave; but down converted. Now, we will get the superposition of multiple waves when we pass this signal. The outputs we see are *cosAcosB* and *cosAsinB* which can be expressed as shown below:

$$cosAcosB = \frac{1}{2}\left(\cos(A-B) - \cos(A+B)\right)$$

$$cosAsinB = \frac{1}{2}\left(\sin(A+B) + \sin(A-B)\right)$$

The topology for the switch mixer is as given below:



We add a bias voltage so that the gate of the MOSFET isn't in cut-off mode. We also ensure that there is an R_{bias} big enough that no current from V_{osc} flows through it; and C_c so low that no V_{bias} current flows through it. Therefore, we took the values R_{bias} as 100k ohm and C_c to be 10n.

As mentioned earlier, the gate of the MOSFET should not be in cut-off mode. Multiplication of two signals in the mixer is only possible if the MOSFET isn't in cut-off mode. We ensure this by adding Bias voltage. For NMOS in LTSpice we took this value to be at 1V. For the MC14007be IC the Bias is observed to be. **1V.** Here V_{osc} is either 500mV, 100kHz sine wave, or cosine wave.

We can calculate Vgs = V_{osc} - V_{in} + V_{BIAS}

The output measured can be determined as $I_{DS} \times R_L$. (Given value of R_L = 1kΩ)

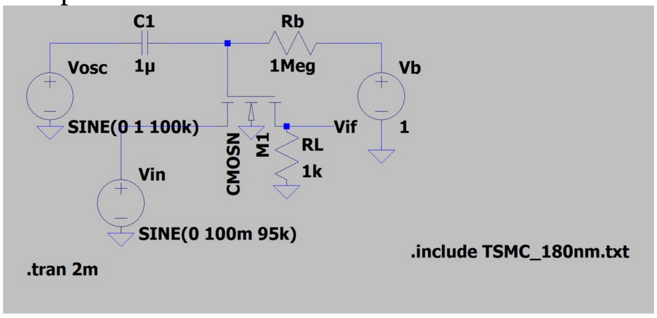
The expression for I_{DS} in saturation region is given by: -

$$I_{DS} = \frac{1}{2}\mu_m C_{ox}(V_{GS} - V_{TH})$$

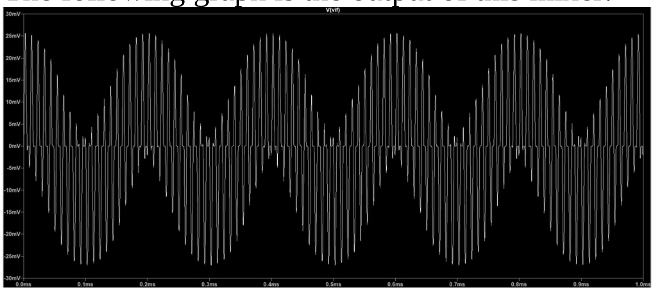
Now putting V_{GS} expansion into the equation; we get-2($V_{OSC} \times V_{in}$) term as part of the expression for I_{DS} which is the required output.

Thus, the mixer functions as a black box that multiplies two input signals sent as inputs.

The schematic diagram for the following circuit in LTSpice:

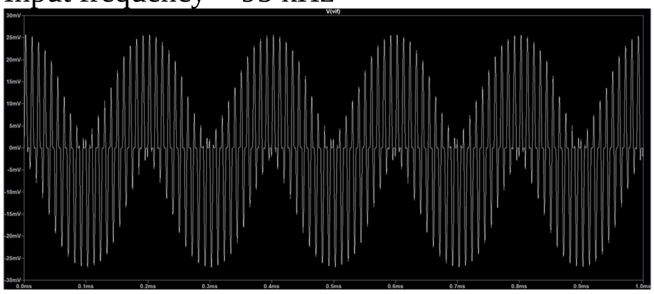


The following graph is the output of this mixer:

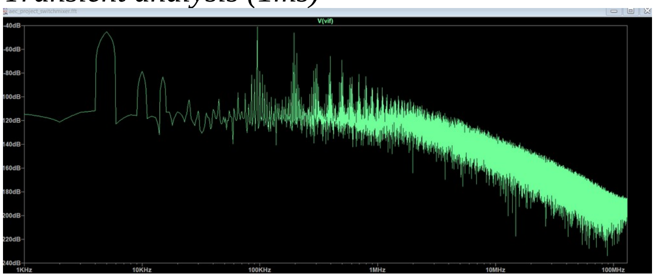


Now, we observe the different output waves when the input waves change:

- Input frequency = 95 kHz

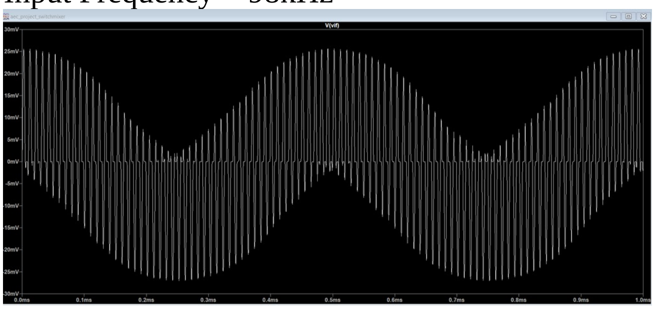


Transient analysis (1ms)

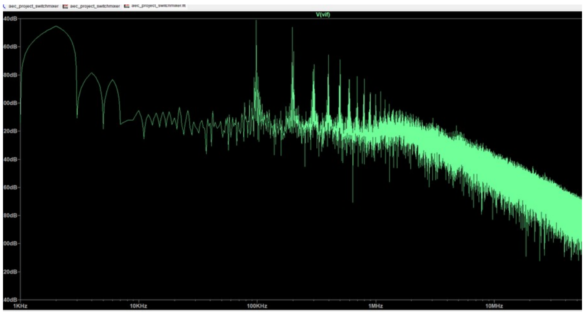


Fast fourier transformation

- Input Frequency = 98kHz

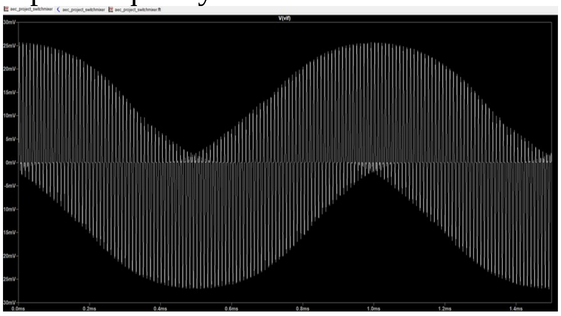


Transient Analysis(1ms)

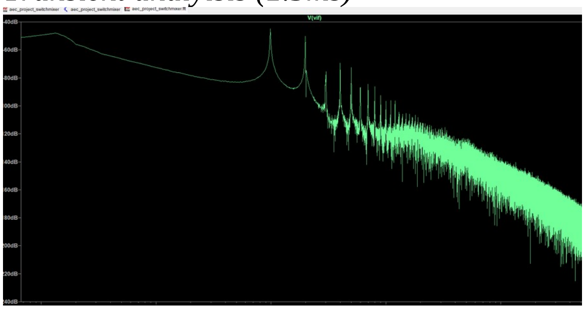


Fast forurier transformation

- Input Frequency = 99kHz

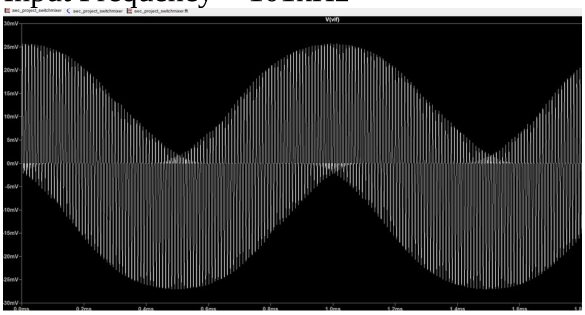


Transient analyisis (1.5ms)

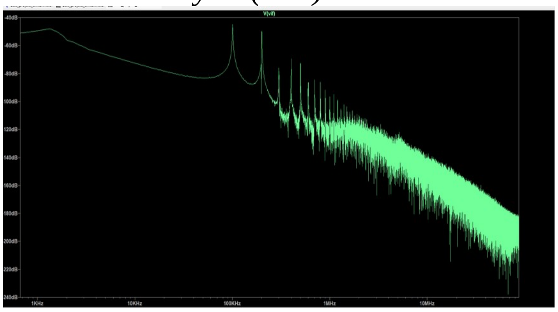


Fast fourier transformation

- Input Frequency = 101kHz

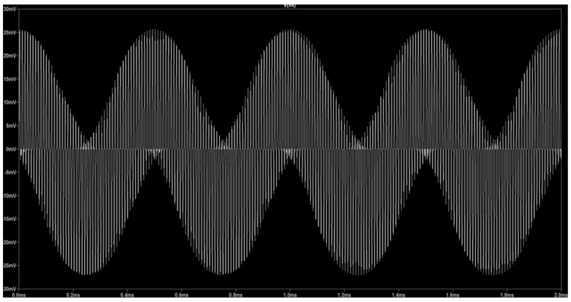


Transient Analysis (2ms)

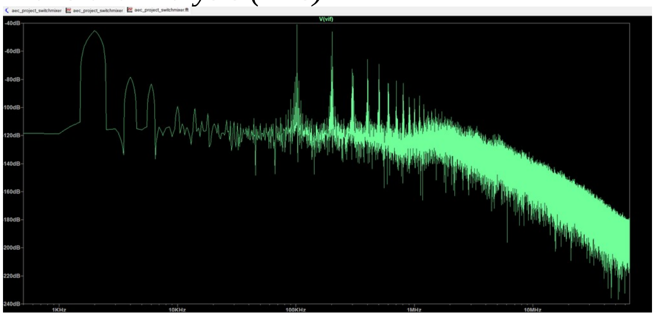


Fast Fourier Transformation

- Input Frequency = 102kHz

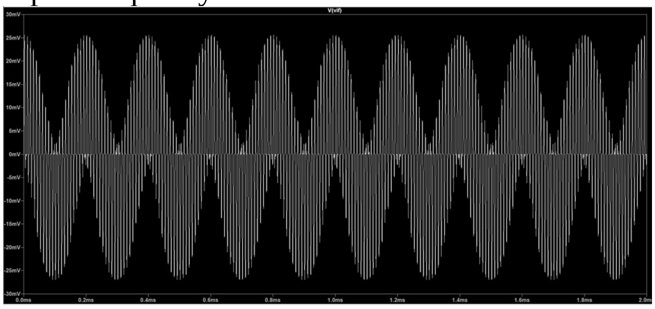


Transient Analysis (2ms)

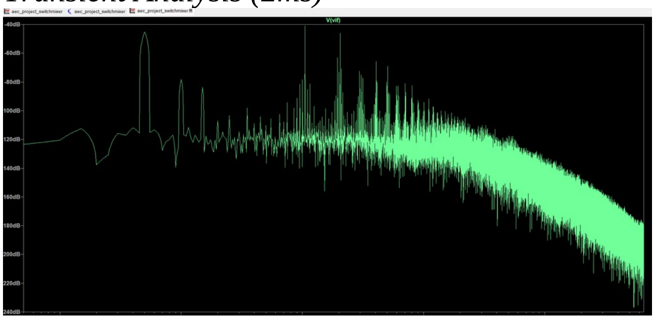


Fast Fourier Transformation

- Input Frequency = 105kHz



Transient Analysis (2ms)

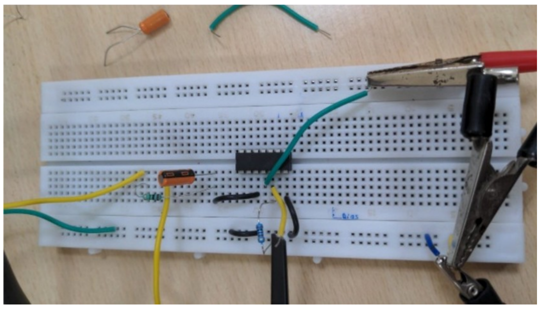


Fast Fourier Transformation.

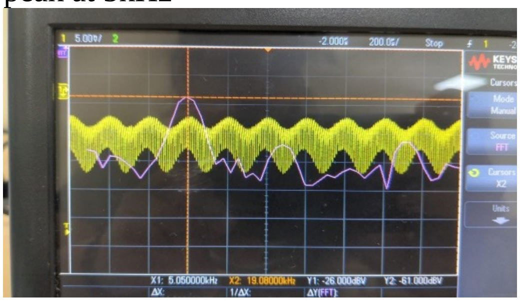
The shape of the graph is due to the switching action of the mixer. The value of V_{BIAS} is chosen in such a way that when the oscillator signal adds up to the biasing voltage, The MOSFET enters the cutoff region at regular intervals (when Vosc is negative that is.) At these points; this graph appears to be approaching zero. It doesn't reach zero, because of the high frequency of the signals supplied. It doesn't have the time to reach zero, before the mosfet goes back into the saturated zone and multiplies.
We can analyze the FFT signal too. When there is either a sum or a difference in the

input frequencies, we see a significant rise in the graph.
Essentially we can see that this given circuit acts as a mixer, and a switch simultaneously. That is, when the MOSFET is in the saturated region it mixes the two signals. When the mosfet is in cutoff mode, it doesn’t.

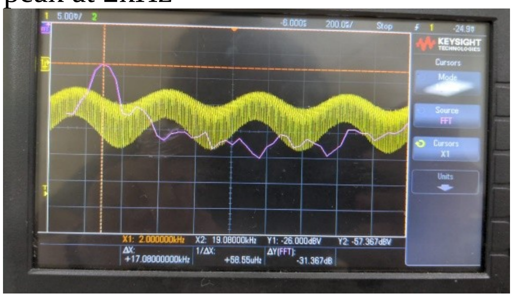
The circuit observed in the lab:



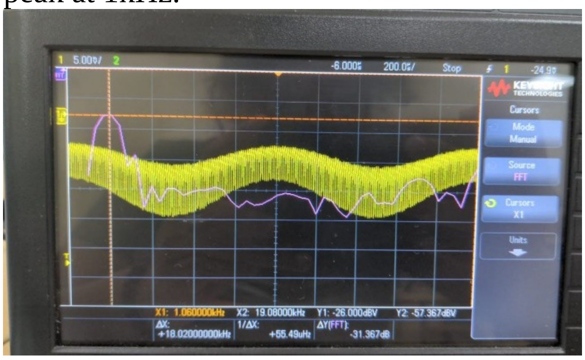
Input frequency = 95kHz, FFT observes peak at 5kHz



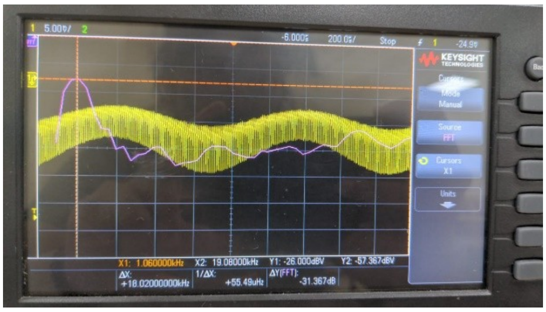
Input frequency = 98 kHz, FFT observes peak at 2kHz



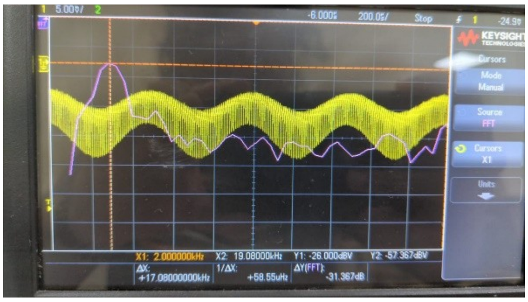
Input frequency = 99kHz, FFT observes peak at 1kHz.



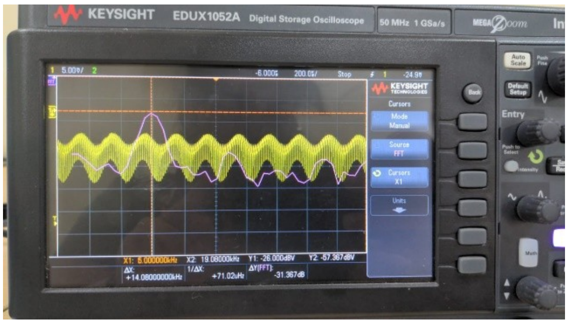
Input frequency = 101kHz, FFT peak observed at 1kHz.



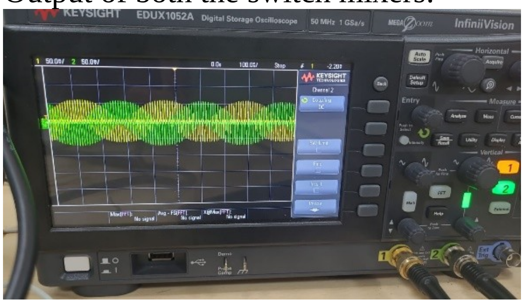
Input frequency = 102kHz, FFT peak observed at 2kHz.



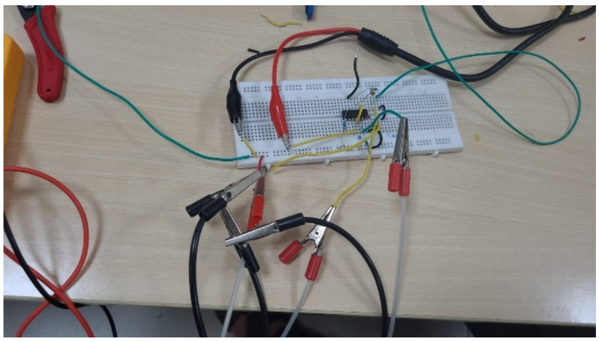
Input frequency = 105kHz, FFT peak observed at 5kHz



Output of both the switch mixers:

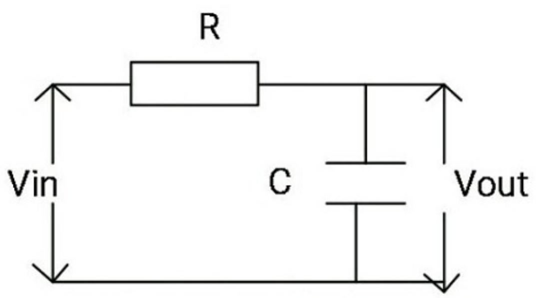


Circuit of both mixers:



C. *LOW PASS FILTER*

By definition, a low-pass filter is a circuit offering easy passage to low-frequency signals and difficult passage to high-frequency signals. This filter circuit allows only low pass frequency components and blocks all other higher frequency components. The name LPF itself indicates low range frequency. This type of filter circuit allows the frequency components of the signal less than the cut of the frequency range of a signal. The gain of the low pass filter is inversely proportional to the frequency. If the frequency of an input signal increases, the gain of the circuit decreases and also becomes zero at the transition band end-stage. So, the bandwidth is also limited. But, in practice, the LPF allows the low range frequency components of a signal even if it reaches slightly after the cut off frequency.



Generic diagram of a capacitive type LPF

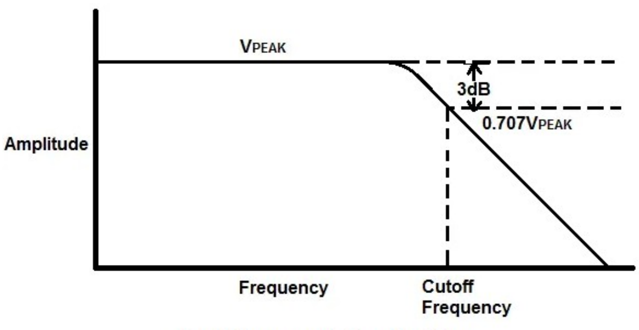
Cut-off frequency

All low-pass filters have a certain cutoff frequency, above which the output voltage drops below 70.7% of its input voltage. The frequency at which the magnitude response is 3 dB lower than the value at 0 Hz, is known as the Cutoff Frequency of a low pass filter.

It is calculated as follows:

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

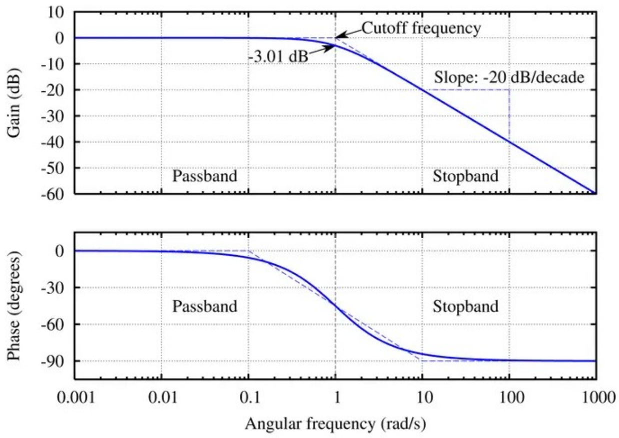
$$20\log\left(\frac{1}{\sqrt{1+(2\pi fRC)^2}}\right) = -3$$



Cutoff Frequency of a Low Pass Filter

Until the Cut-off Frequency point is reached, all of the input signals pass directly to the output, which results in a unity gain. This happens when the reactance of the capacitor is large at low frequencies and prevents any current flow through the capacitor. The response of the circuit decreases to zero at a slope of -20dB/ Decade “roll-off” after this cut-off frequency point.

The frequency point at which the capacitive reactance and resistance are equal is known as the cutoff frequency of a low-pass filter.



Example of a Bode Plot

A graph that is commonly used in control system engineering to determine the stability of a control system is known as a Bode plot. The Bode plot outlines the frequency response of the system by two graphs – the Bode magnitude plot (which shows the magnitude in decibels) and the Bode phase plot (which shows the phase shift in degrees). In the Bode plot, the corner/cut-off frequency is defined as the frequency at which the two asymptotes meet each other or cut each other.

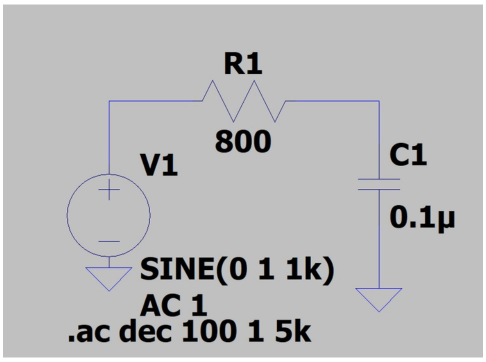
We used the values:

R = 853Ω

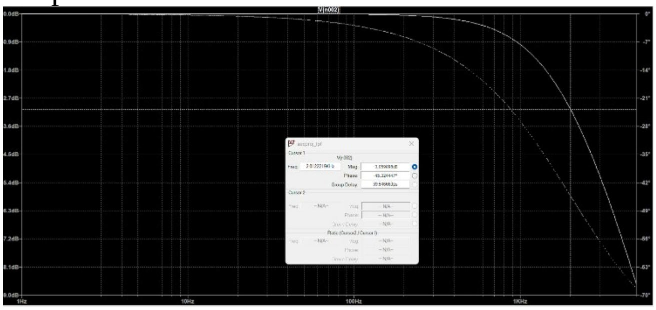
C = 0.2μF

Ideally, 800 Ω and 0.1 μF are used but since, our circuit showed output with these values, we used these values.

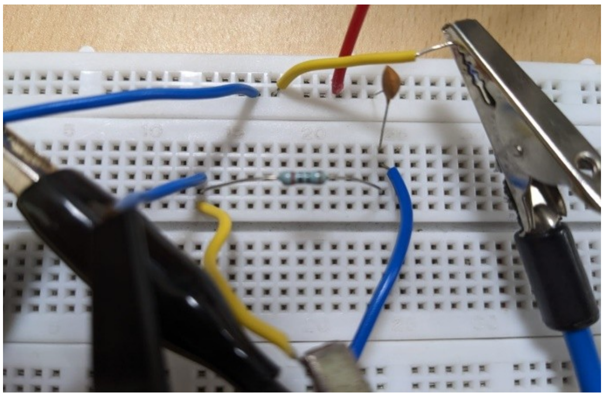
LTSPICE DIAGRAM:



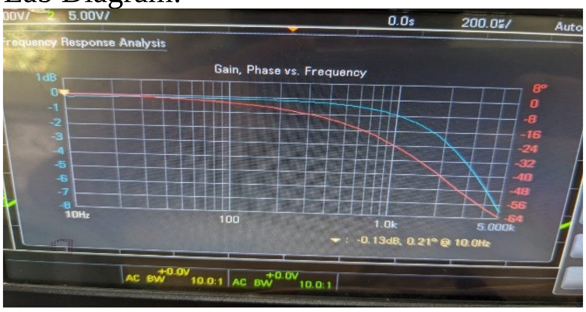
Graph:



Lab circuit:



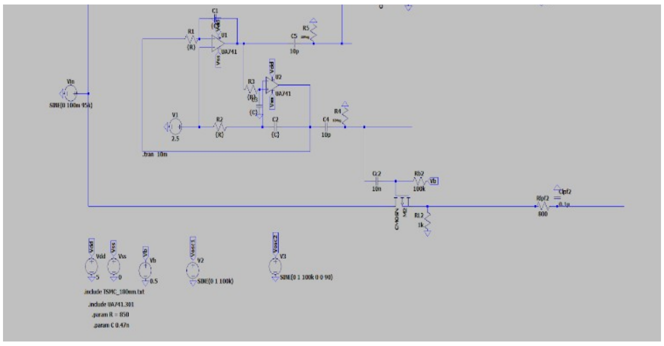
Lab Diagram:



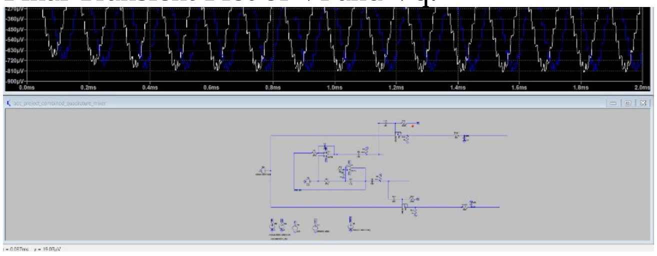
THE FINAL CIRCUIT

The following are the LTSpice and the in real life observations of the final quadrature down converter. In our simulation we sent in a signal of amplitude 100mV and frequency = 95kHz. This is the input. In our real life circuit(lab circuit) we observed that the Vosc (oscillating outputs from the quadrature oscillator) are 92kHz and 90kHz respectively. So, we took in the input of 100kHz. In an ideal scenario our output frequencies should be 7kHz-10kHz, in accordance to the working of the switch mixer discussed earlier. (if we account for error)

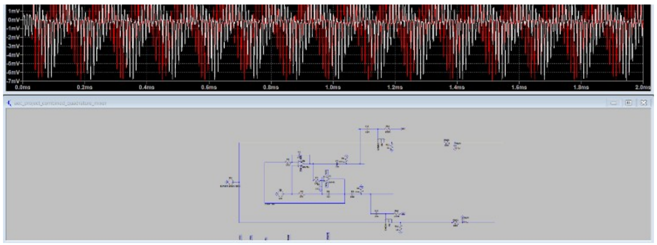
Circuit:



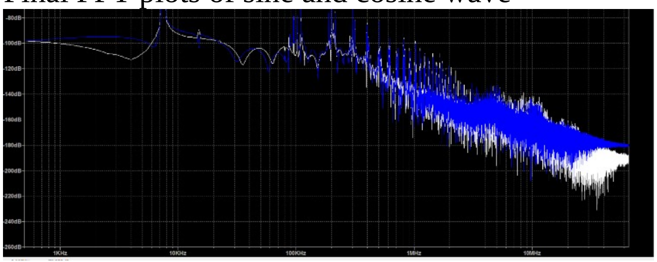
Final Transient Plot of Vi and Vq:



Final transient Plots of switch mixer:



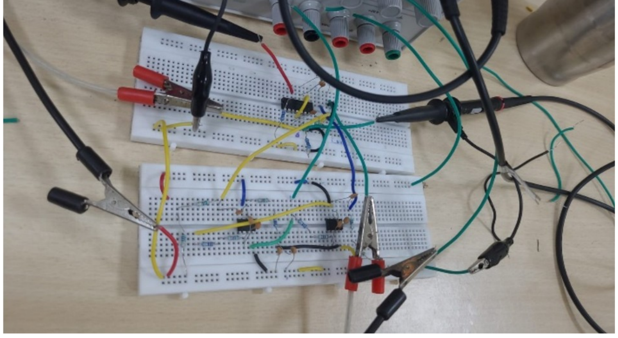
Final FFT plots of sine and cosine wave



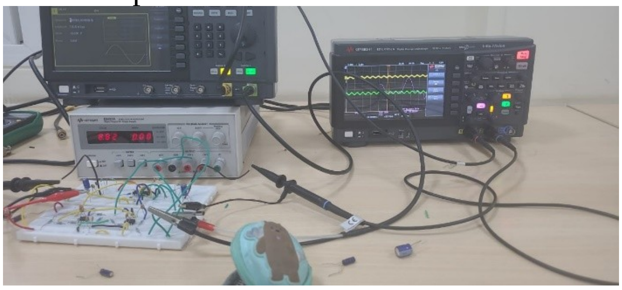
The final frequency peak is at 7.51kHz.

Lab Hardware:

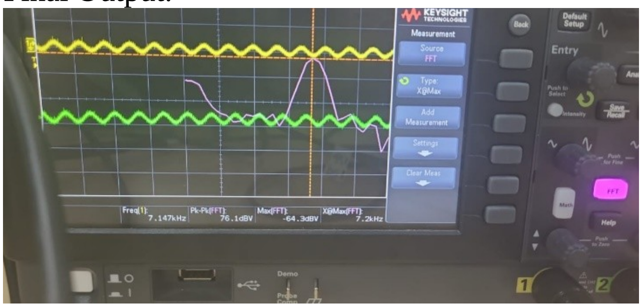
Our Final Circuit:



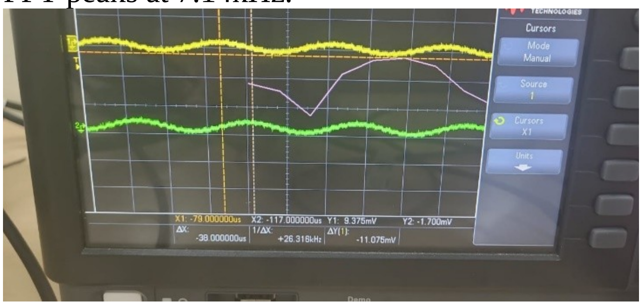
Final Setup:



Final Output:



FFT peaks at 7.14kHz.



The final phase difference:

Difference of peaks in time axis: 38u

Hence, final phase difference is: 97 degrees.

Values:

Parameters	Simulated	Observed
R in oscillator	850 ohm	850 ohm
C in oscillator	0.47 nF	0.2pF

Cc	10u	10u
Rb	10Meg	10Meg
Vbias	1V	1V
Vin	100mV	100mV
f_{in}	95kHz	100kHz
f_{osc}	101 kHz	91kHz (aprox)
$A_{osc\text{-}I\ phase}$	1Vpp	925mVpp
$A_{osc\text{-}Q\text{-}phase}$	1Vpp	831mVpp
IF	7.51kHz	7.14kHz
Final Phase	90 degrees	97 degrees

APPLICATIONS

[1] Wireless Communication Systems: Down converters play a crucial role in wireless communication systems, such as cellular networks, satellite communication, and wireless data transmission. In these systems, high-frequency signals received from antennas need to be converted to lower intermediate frequencies (IF) for further processing. Down converters are used to shift the frequency spectrum of incoming signals, enabling efficient filtering, amplification, and demodulation.

[2] Satellite Television: Down converters are employed in satellite television systems for signal reception and decoding. Satellite signals transmitted at high frequencies are converted by down converters to lower intermediate frequencies before being demodulated and processed by the set-top box or satellite receiver. This frequency conversion allows for efficient signal processing and extraction of audio and video content.

[3] Medical Imaging: In medical imaging techniques such as magnetic resonance imaging (MRI) and positron emission tomography (PET), down converters are used to shift the frequency of the received signals. By converting the high-frequency signals from the imaging device, down converters make it easier to amplify, filter, and process the signals accurately, enabling the creation of detailed images for diagnostic purposes.

[4] Test and Measurement Equipment: Down converters find extensive use in various test and measurement applications. In spectrum analyzers, for instance, down converters help analyze high-frequency signals by converting them to lower frequencies within the analyzer's operating range. This enables accurate frequency analysis, modulation measurements, and distortion analysis of signals.

ACKNOWLEDGMENT

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[1] Design of Analog CMOS integrated Circuits by Behzad Razavi *Chapter 2 and Chapter 4*

[2] Microelectronic Circuits by Adel S. Sedra, Kenneth C. Smith, Chapter 2 and Chapter 14.

[3] “Quadrature Down-converter for Wireless Communications” by Farsheed Mahmoudi

[4] electrical4u.com – Low-pass filter