AEC Project: Quadrature Down Converter

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***Abstract*—In this project, we are making a Quadrature Down Con- verter (QDC) that is commonly used in modern day wireless receivers. The main purpose of the Quadrature down converter is to do frequency down conversion of the signal (which is already up converted and also have some noise with it).**
We first simulated the circuit using LTSpice software,and then implemented the circuit on a breadboard.

I. Introduction(Utility of the circuit)

Direct-conversion receivers offer advantages like lower current drain and simpler image-rejection tasks, making them suitable for digital cellular telephones and miniature radio messaging systems. This process enables efficient signal processing, spectral efficiency, and easier modulation/demodulation, crucial for modern wireless communication systems. The I and Q components are orthogonal to each other, meaning they are independent and do not interfere with each other. This orthogonality facilitates the transmission of more data within the same bandwidth, effectively doubling the achievable data rate. Moreover, by separating the signal into these orthogonal components, it becomes easier to distinguish and decode multiple signals in complex communication environments.

II. Quadrature Oscillator design

A. Description of the circuit

A quadrature oscillator circuit is a type of electronic oscillator that generates two output signals that are 90 degrees out of phase with each other. This phase relationship is often referred to as being ”in quadrature.”
This oscillator consists two Op-amps,producing two sinusoidal signals at 90 degrees phase difference at their outputs respectively. The circuit oscillates at particular frequency, which is picked up from the thermal noise in the circuit.
It consists of two integrator blocks, positive and negative integrator respectively. The sine wave generated at one input is integrated into a cosine wave and this cosine wave is again integrated into a sine wave.
There are resistors and capacitors across the feedback path.

B. Topology and Calculations

The circuit topolgy consists of two integrator blocks,connected together.
Let us label the Op-amps as 1 and 2 respectively, and call the outputs at their output ports to be V_{os} and V_{oc} respectively, denoting sine and cosine waves.

$$V_{+2} = \frac{V_{os}}{1 + R_2C_2S} \tag{1}$$

$$V_{oc} = V_{+2} \cdot (1 + \frac{1}{R_3C_3S}) \tag{2}$$

$$V_{os} = \frac{-V_{oc}}{R_1SC_1} \tag{3}$$

For stable oscillations the closed loop gain should be unity.

$$(\frac{1}{1 + R_2C_2S}) \cdot (\frac{R_3C_3S + 1}{R_3C_3S}) \cdot (\frac{-1}{R_1C_1S}) = 1 \tag{4}$$

Now for frequency domain $S = j\omega$
If we choose $R_1C_1 = R_2C_2 = R_3C_3 = RC$.

$$\frac{-1}{(RCj\omega)^2} = 1 \tag{5}$$

$$\omega = \frac{1}{RC} \tag{6}$$

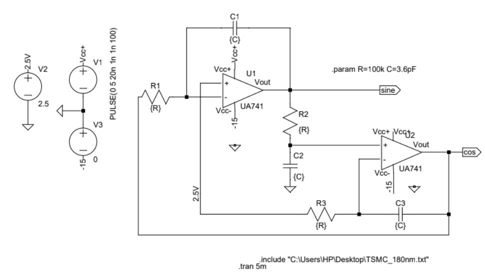

Fig. 1. Quadrature Oscillator

For our goal of $100\,\mathrm{kHz}$ frequency signal, we choose R and C as $102.75\,\mathrm{k\Omega}$ and $6.5\,\mathrm{pF}$ respectively.
But, we observe less frequency than the desired at the output due to op-amp imperfection. To fix this issue, from calculated values of R and C, we can decrease the resistance keeping capacitance constant till we observe the desired output frequency.

C. LT Spice Simulations

The following is the time domain output of the quadrature oscillator.

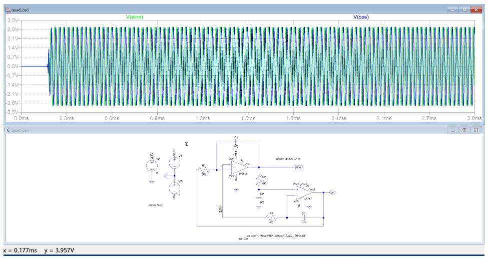

Fig. 2. Quadrature Oscillator output

It generated two sinusoidal waves at a phase shift of 90 degrees.

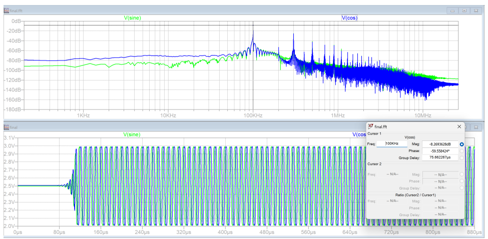

Fig. 3. Quadrature Oscillator output

III. SWITCH(MIXER) DESIGN

A. Description

A simple MOSFET can be used as a switch (mixer), where the oscillator signal is applied to the gate of the device, input is applied at the source and the intermediate frequency output is taken at the drain end. The basic idea behind the circuit is to take benefit of the switching action on the transistor.

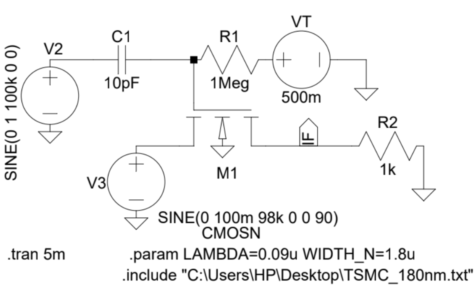

Fig. 4. Quadrature Oscillator

B. Topology and calculations

We have used the NMOS in the following configuration. A coupling capacitor is used to allow only ac signals to pass through. We have used a large value of $\mathrm{R_{bias}} = 1M\Omega$ to stop any leakage current that might occur. This $\mathrm{R_{bias}}$ and coupling capacitor form a high pass filter, so we have choosen the valur of capacitor such that the our frequency of interest is above the cutoff. We used Capacitor value to be $10\,\mathrm{pF}$. The coupling capacitor is used so that the DC noise from the oscillator is blocked. The bias voltage is taken approximately equal to the threshold value, which helps in achieving mixing opertaion. The V_t value was taken from the assignment done earlier. The design parameters of the mosfet are LAMBDA=0.09u and WIDTHN= 1.8u

C. Working of the mixer

The DC bias of the mosfet is V_t. The gate voltage can be considered as a super-imposition of the DC bias and the AC input signal.

$$V_{gs} = V_t + V_{osc} \tag{7}$$

For mosfet to turn on $V_{gs} \geq V_t$ Thus we can say that Mosfet is turned on when:

$$V_{osc} \geq 0 \tag{8}$$

When the mosfet is on($V_{osc} \geq 0$, positive half cycle of the oscillator input) it acts like a switch , and the signal at source terminal appears at the drain terminal, which is taken at the output.

$$V_d = \frac{V_s R_l}{R_l + R_{on}} \tag{9}$$

$$V_d = \frac{V_s}{1 + \frac{1}{k(V_{gs} - V_{th})R_l}} \tag{10}$$

$$V_d = \frac{1}{1 + \frac{1}{k(V_{gs} - V_{th})R_l}} \tag{11}$$

Let's call $kR_l = M$

$$V_{out} = \frac{V_{in}}{1 + \frac{1}{MV_{osc}}} \tag{12}$$

Since $M \ll 1$
$V_{out} = V_{in} V_{osc} M$
When the mosfet is off, ground voltage appears at the output.

Due to high frequency with which the mosfet is turing on and off. The mixing action can be seen as multiplication of V_{in} with a square wave with frequency as that of V_{osc} going from 0 to 1.

The square wave esentially contains the frequency components of the Oscillator signal. This switching action is equivalent to multiplication as we get frequency of output as $(\omega_{osc} - \omega_{in}), (\omega_{osc} + \omega_{in})$ and the multiplication of odd harmonics of V_{osc}.

Writing equations for the mosfet when on in Linear mode:

D. LT Spice Simulations

The following are the output of mixing V_{in} and V_{osc} both in time domain and frequency domain.

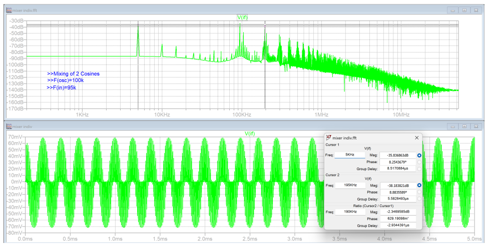

Fig. 5. Cosine waves of 100k and 95k frequency

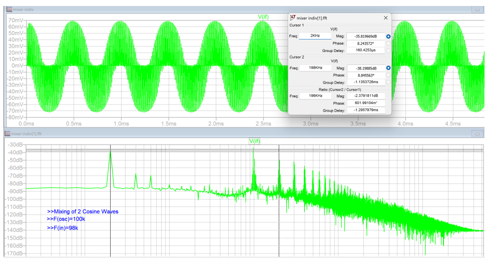

Fig. 6. Cosine waves of 100k and 98k frequency

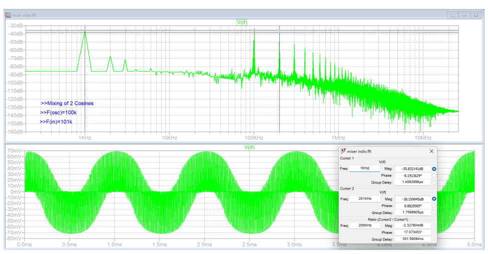

Fig. 7. Cosine waves of 100k and 101k frequency

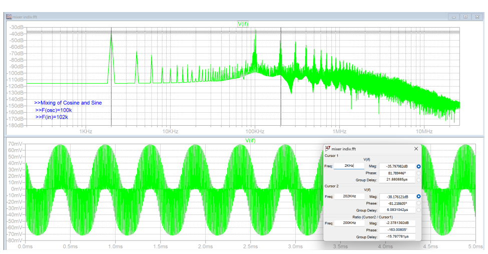

Fig. 8. sine wave of 100k and cosine of 102k frequency

We observed the desired output as expected in both FFT and time domain plots.

IV. Low pass filter design

A. Description

A basic low pass filter can be designed using a resistor and a capacitor with cutoff frequency of $\frac{1}{2\pi RC}$

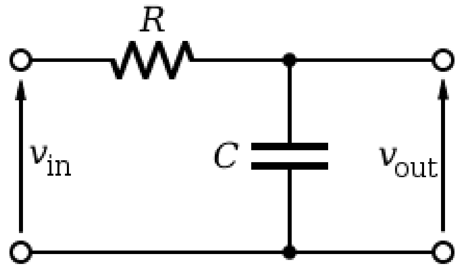

Fig. 9. basic low pass filter

B. Topology and Calculations

The circuit consists of a resistor connected in series along with a capacitor. The input is applied at the one of the resistor and output taken at the node between capacitor and resistor. $V_{out} = V_{in} \cdot \frac{1}{1+RSC}$

For frequency analysis we put $S = j\omega$.

If $|j\omega RC| \ll 1$, we get $V_{out} = V_{in}$

For 3dB frequency $|j\omega RC| = 1$,at this instant $V_{out} = \frac{1}{\sqrt{2}} V_{in}$

For cutoff frequency at 2kHz we chose R= $7.5\,\mathrm{M\Omega}$ and C= $10.61\,\mathrm{pF}$. We chose a high value of resistance so that it doesn't affect the output of the mixer being a high impedance value, lower values were causing a change in mixer output due to low input impedance.

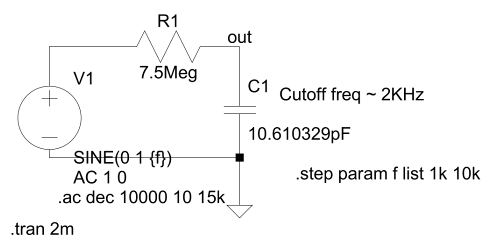

Fig. 10. low pass filter

C. LT spice simulations

The following is the bode magnitude plot of the low pass filter.

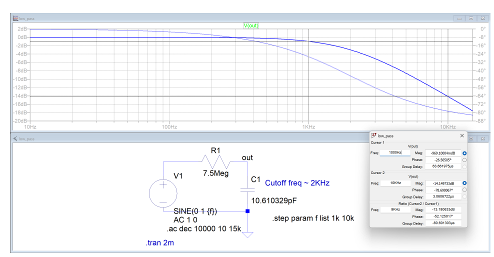

Fig. 11. bode plot of LPF with cutoff frequency at 2Khz

The following is the transient response for input frequencies at 1Khz and 10khz, we can clearly see low pass filter action from it.

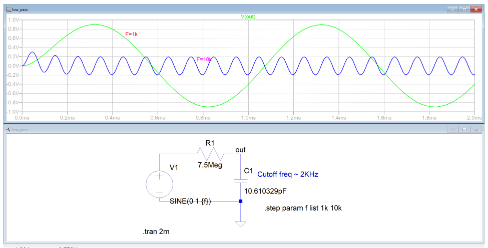

Fig. 12. Transient analysis for two input signals at 1khZ and 10Khz

D. Mixer and Filter connected together

We had already made mixer in previous section. We now feed the output of the mixer into the input of the low pass filter.
From our previous knowledge of the mixer we know that the output of it had frequency componets at $(\omega_{osc} - \omega_{in})and(\omega_{osc} + \omega_{in})$

Now thorugh the low pass filter only that frequency will pass which is below the cutoff frequency of the low pass filter, the rest of the frequencies will be blocked. For our frequencies of interest of the input signal and oscillator output the frequency of $\omega_{osc} - \omega_{in}$ will pass through.

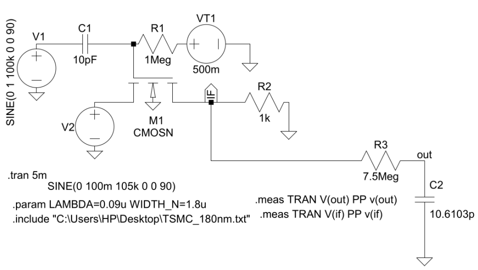

Fig. 13. Mixer connected with low pass filter

E. Lt spice simulations

The following are the time and frequency domain response of the circuit

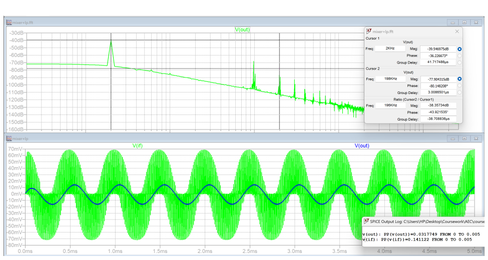

Fig. 14. Cosine waves of 100k and 98k frequency

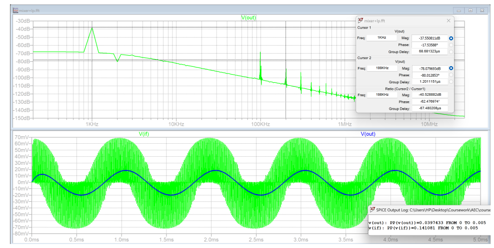

Fig. 15. Cosine waves of 100k and 99k frequency

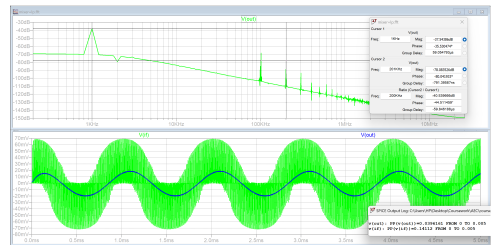

Fig. 16. Cosine waves of 100k and 101k frequency

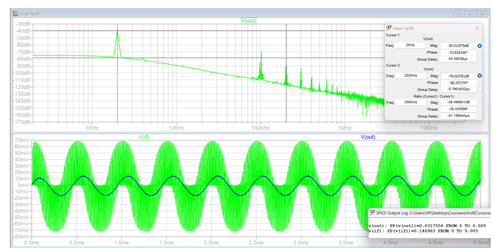

Fig. 17. Cosine waves of 100k and 102k frequency

We observe the frequency component of $|\omega_{osc} - \omega_{in}|$ to be dominant and the frequency of $|\omega_{osc} + \omega_{in}|$ to be supressed by the low passs filter.

V. Complete circuit prototype design

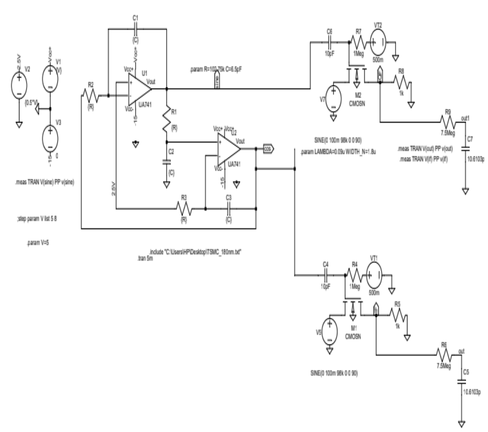

Fig. 18. Complete circuit with all the components connected together

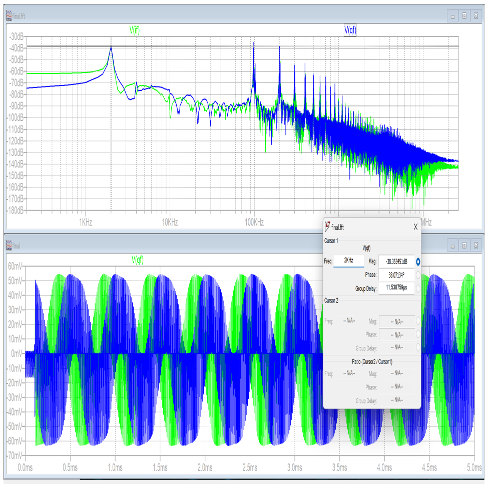

Fig. 19. IF,IQ

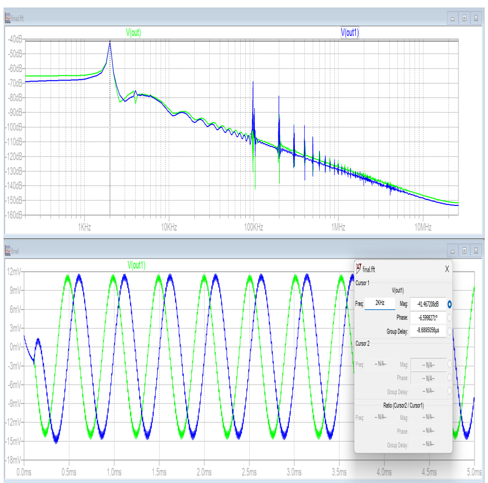

Fig. 20. IF final,QF final

VI. Hardware results

A. Quadrature oscillator

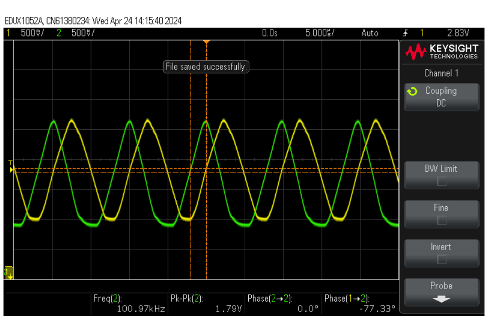

Fig. 21. Quadrature oscillator output with 2 sinusoids at 100kHz

B. Mixer

Mixer circuit

TABLE I
Comparison between simulation and hardware

Quantity	Measured	Simulated
Amplitude	$1.79V_{pp}$	$2V_{pp}$
Frequency	100.97 kHz	100kHz
Phase	77.13	89

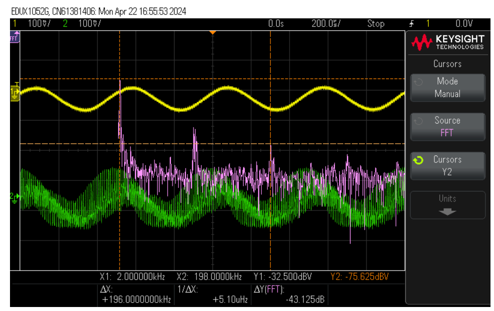

Fig. 22. Mixing of two signals at 100kHz and 98kHz

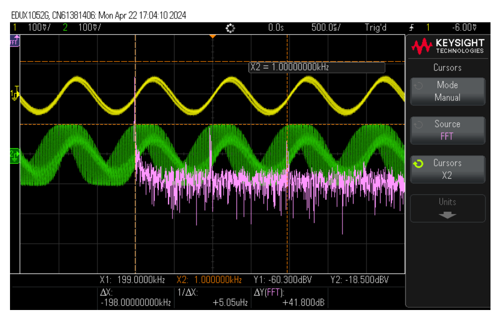

Fig. 23. Mixing of two signals at 100kHz and 99kHz

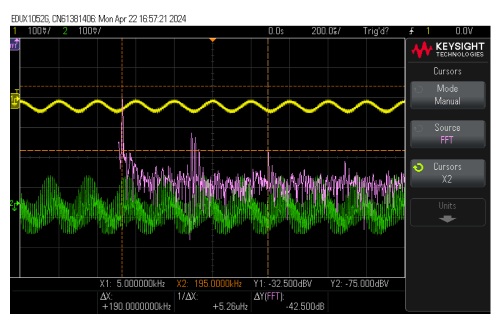

Fig. 24. Mixing of two signals at 100kHz and 105kHz

We could clearly observe the frequency component below 2Khz to be dominant.

C. Low pass filter

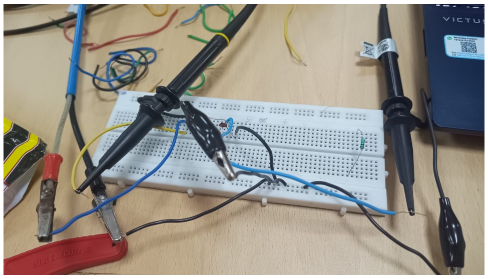

Fig. 25. Lab circuit

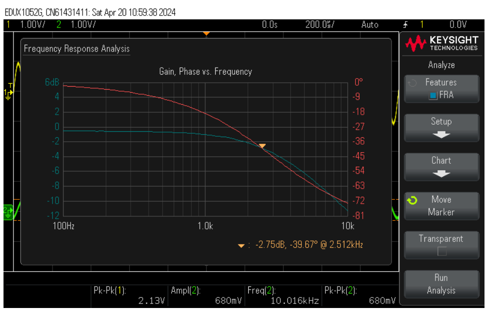

Fig. 26. Bode plot of Low pass filter

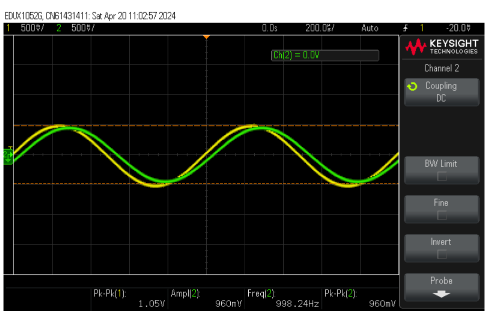

Fig. 27. Output and input signal for input at 1kHz

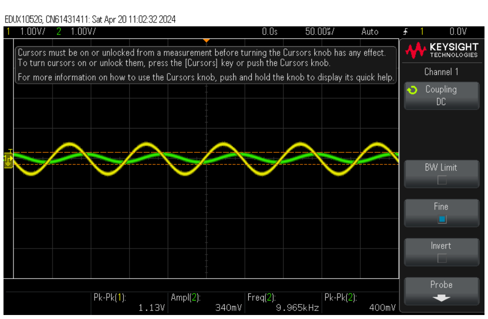

Fig. 28. Output and input signal for input at 10kHz

We could clearly observe the low pass filter action for 1khz and 10kHz input frequencies.

D. Final circuit with all components connected together

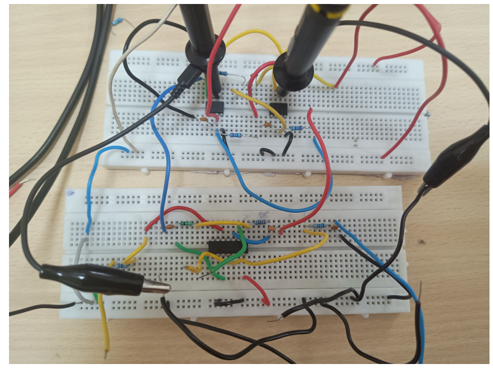

Fig. 29. Lab circuit

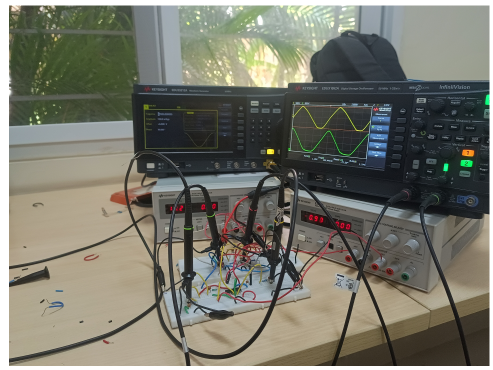

Fig. 30. Lab circuit and V_{IFI} and V_{IfQ}

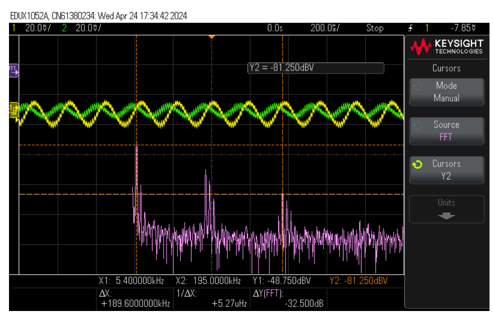

Fig. 31. Input siganl at 95khZ

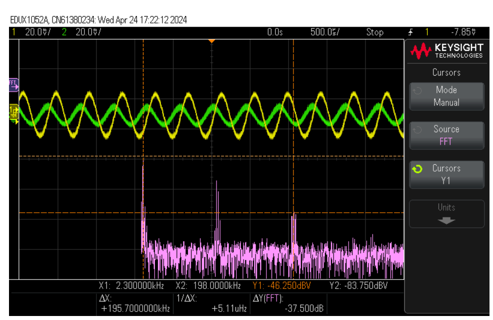

Fig. 32. Input siganl at 98khZ

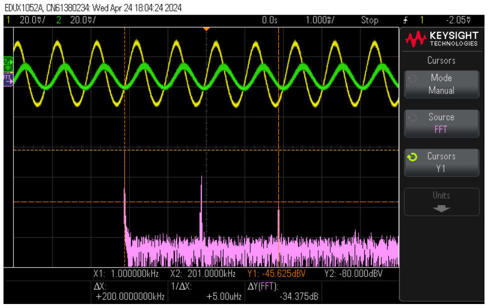

Fig. 33. Input siganl at 99khZ

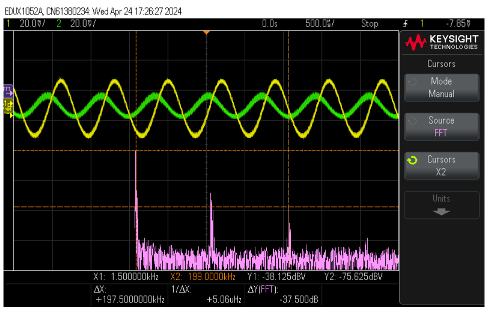

Fig. 34. Input siganl at 99khZ

TABLE II
PERFORMANCE SUMMARY AND COMPARISON

Parameters	Simulated	Measured
Oscillator Frequency	100.97 kHz	100Khz
Oscillator Amplitude(I-phase)	$2V_{pp}$	$1.79V_{pp}$
Oscillator Amplitude(Q-phase)	$2V_{pp}$	$1.79V_{pp}$
Input frequency	99.98kHz	100Khz
Supply	10.69V	5V
V_{bias}	980mV	500mV
C_c	10pF	10pF

REFERENCES

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[2] Behzad Razavi, Fundamental of Microelectronics

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[5] Class notes

[6] Project description pdf