

Quadrature Down Converter

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Abstract—Transmitting low-frequency signals is practically impossible as it would require the antenna length to be very large, and it would also cause a lot of information loss over the channel; due to this we combine this original signal with a carrier wave of very high frequency such that the antenna length and the error in transmission both decrease; now such a wave is generated by producing frequency of sum of the original signal and the carrier frequency and then it is transmitted. We at the receivers end are now going to convert this received signal into the original signal

I. INTRODUCTION

We obtain this result which is expected from the receiver by using a device called the Quadrature Down Converter.

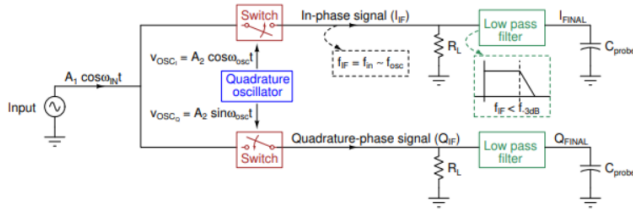


Fig. 1. Quadrature Down Converter

II. ITS WORKING

It recovers the original signal by subtracting the carrier frequency from the received signal. It achieves its purpose with the help of 3 main parts. These are listed below.

- 1) Quadrature Oscillator
- 2) Mixer Circuit
- 3) RC Low Pass Filter

III. QUADRATURE OSCILLATOR

A. Intro To A General Oscillator:

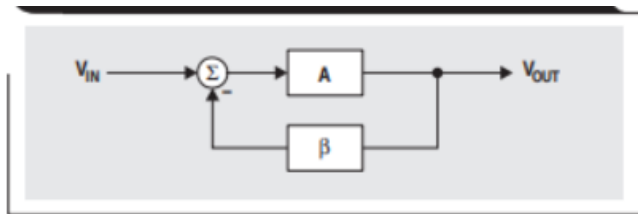


Fig. 2. General depiction of an Oscillator

We can represent all oscillators using the image above, which gives the transfer function as

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta}$$

$|A\beta|$, the magnitude of the loop gain affects the circuit's behavior:

- If $1 + A\beta \neq 0$:
 - If $1 + A\beta < A$, the circuit acts as an amplifier
 - If $1 + A\beta > A$, the circuit attenuates the input signal
- If $1 + A\beta = 0 \Rightarrow$ this implies $A\beta = -1$: Then

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{0}$$

which implies even small V_{in} (e.g., internal noise of the circuit) can be significantly amplified.

- This is called the **Barkhausen criterion**, $A\beta = -1$ By complex math, this is equivalent to $A\beta = 1 \angle -180$.
- The -180 phase shift criterion applies to negative feedback systems, and 0 phase shift applies to positive feedback systems.

So, initial small noise gets amplified which eventually becomes a sine wave or cosine wave. For this to happen, the modulus of gain should initially be slightly greater than 1 to allow the waveform to grow. Later, this is again made to 1 to maintain the signal.

Now that we have made $1 + A\beta = 0$ we see that the circuit can now behave in 3 different ways.

- It could gradually increase and fully saturate to a final value, here the non-linear elements present in the circuit would play no role
- It could saturate, stay there for a while and then a sudden change could make the circuit reach negative saturation and so on, which would effectively produce square or triangular waves, the circuit would have sudden changes brought about by the non-linear elements preset in it and the circuit could possibly have positive feedback
- It could slowly saturate to positive voltage and again reach to the negative saturation, slowly again. This would give rise to sine and cosine kind of waves, the nonlinear elements would generate gradual changes consisting of

both positive and negative feedback (this is the kind we want)

As the amplitude saturates near the opamp's voltage swing limits:

- The modulus of gain should become slightly less than 1 to deamplify the now saturated voltage.
- This self-limiting behavior is due to the non-linear properties of the op-amp:

This causes the system to naturally limit its amplitude, resulting in a stable sine wave output from an initially noisy and unstable startup.

B. Building the oscillator

Quadrature Oscillator: A quadrature oscillator is a special type of phase-shift oscillator where the RC network is configured to generate two output waveforms that are **90° out of phase** that is sine and cosine waves. It uses **three RC sections**, each contributing a 90° phase shift. The outputs from two op-amps are labeled as sin and cos, indicating their phase relationship.

We use the below Quadrature Oscillator circuit as our basis and build on top of it to meet our requirements.

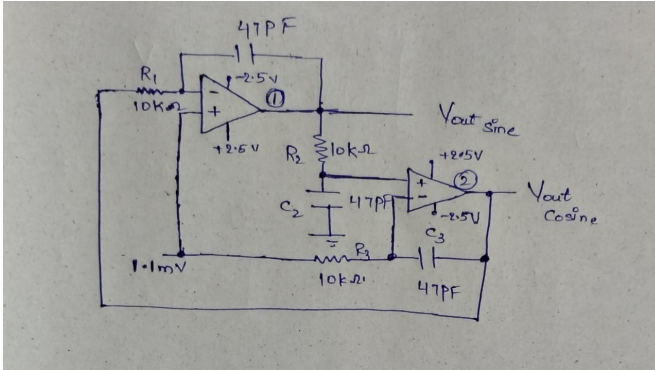


Fig. 3. Quadrature Oscillator

FINDING OSCILLATOR CAPACITOR AND RESISTOR VALUES FOR REQUIRED FREQUENCY OF 100KHz

$$V_{+2} = \frac{1}{1 + R_2 C_2 s} V_{sin} \quad (1)$$

From the concept of Virtual ground

$$V_{-2} = V_{+2} = \frac{R_3}{R_3 + sC_3} V_{cos} \quad (1)$$

$$\Rightarrow V_{cos} = \left(1 + \frac{1}{R_3 C_3 s}\right) V_{+2} \quad (2)$$

From Virtual ground

$$V_{i-} = V_{i+} \quad (2)$$

$$V_{i-} \approx 0 \quad (3)$$

$$\Rightarrow V_{sin} = -\frac{1}{R_1 C_1 s} V_{cos} \quad (3)$$

multiplying (1), (2) & (3) we get,
we analyze the product of individual transfer functions in the loop:

$$H(s) = \frac{1}{1 + R_2 C_2 s} \cdot \frac{R_3 C_3 s + 1}{R_3 C_3 s} \cdot \frac{-1}{R_1 C_1 s} = -1$$

To satisfy the Barkhausen criterion, we set:

$$H(s) = -1 \quad \text{at} \quad s = j\omega_0$$

$$\Rightarrow R_1 C_1 = R_2 C_2 = R_3 C_3 \quad (4)$$

$$f_0 = \frac{1}{2\pi RC} \quad (5)$$

Realizing this circuit in Simulation for a frequency of 100KHz for $R=33.8\text{Kohm}$ and $C=47\text{pF}$, we got a signal of only 75KHz due to paracitic capacitances and the operating region of the OpAmp. Hence using experimentation we have fixed the values of $R=13\text{Kohm}$ and $C=47\text{pF}$, even so we can see that we have obtained a square kind of wave but smoother, and we cannot use this, as we require a sine wave and a cos wave

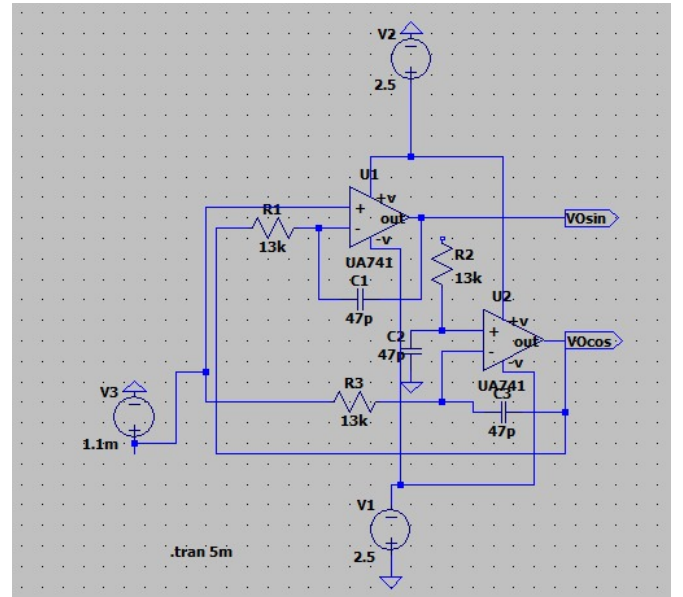


Fig. 4. initial circuit

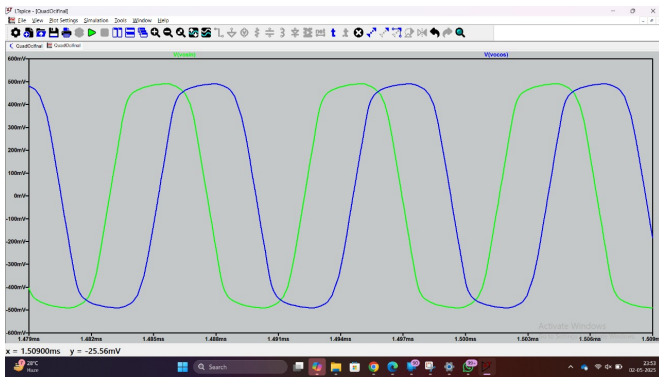


Fig. 5. initial output

C. Reasons for the 500mV saturation of the output

the OpAmp UA741 used is known to not work properly with small voltages, its usual operational point is around 15V, but using it around voltages of 2-2.5V it turns out to have a rail-to-rail voltage of 1V and hence gives out a 1Vpp clipped sine kind of wave, this generation of clipped sine introduces other frequency components in to the output wave. Later on when we use this Op-Amp to build a buffer, we face a voltage drop of 400mV this is also due to the highly

We could change the circuit parameters to achieve this by changing the OpAmp, but instead we do something else

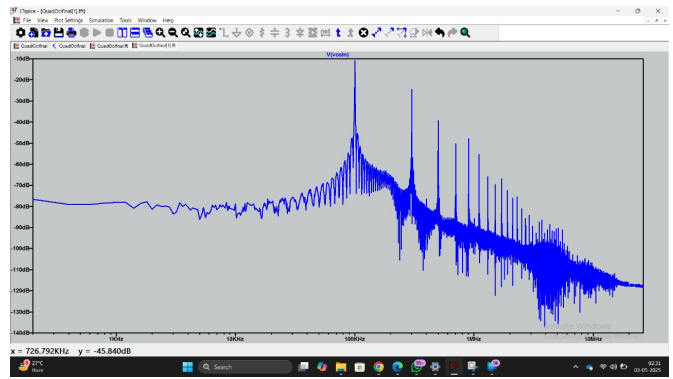


Fig. 6. FFT

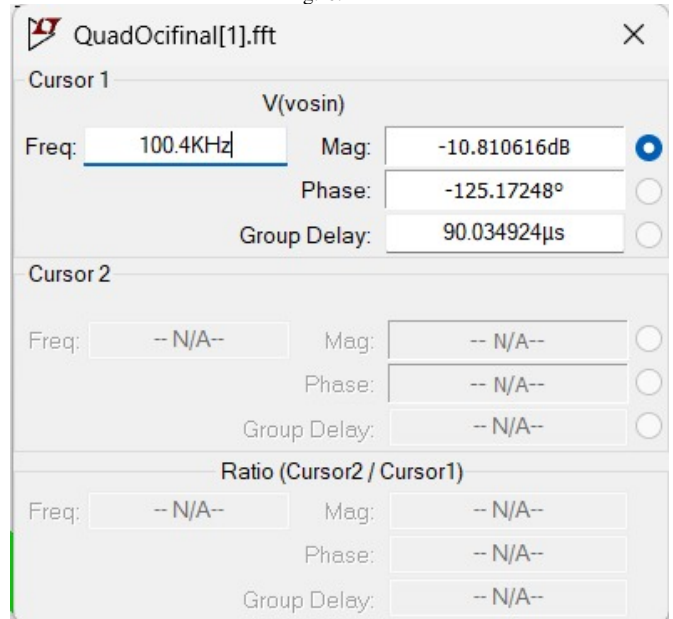


Fig. 7. 100.4KHz FFT result

The **FFT** plot of the current output shows that it does contain the required frequency present in it, we just need to isolate it

We could pass this through a Low-Pass Filter for isolating the required frequency but

Problem: attaching the Low-Pass filter would lead to the filter drawing current from the oscillator which would lead to changes in the Oscillator's working, hence we need the same voltage but isolate the filter from drawing current **Solution:**

1) Buffer Circuit:

- A **buffer circuit** is often used to isolate different stages of the oscillator. It helps preserve the phase shift by preventing loading between stages.
- **High input impedance** ensures that the filter does not load the previous oscillator stage, while **low output impedance** ensures that the buffer can drive the next stage efficiently.
- By inserting a buffer between the oscillator and the subsequent low-pass filter, each RC section behaves inde-

pendently, preserving the characteristics of the oscillator.

- In the real world nothing is ideal. Therefore, the buffer we use has **non infinite input resistance** (finitely large) and **non-zero output resistance** leading to small drop across the buffer circuit. Hence output voltage is slightly less than input.

2) Low-Pass Filter:

- The low-pass filter at the output of the buffer removes unwanted higher frequencies or noise, leaving only the desired oscillation frequency.

Its working:

- The clipped sine/cosine wave from the oscillator contains **extra frequency components**.
- A **passive RC low-pass filter** allows only the fundamental frequency to pass and **attenuates** higher frequencies.
- Since we buffered the signal before filtering, the oscillator's operation is not affected.

3) **NMOS Amplifier with active load (Amplitude Restoration): Problem:** After filtering, the signal amplitude reduces due to the RC network and buffer losses (non-ideal op-amp resistances). Now with the signal amplitude being so low (around 10s of mV) since we need 1Vpp with 100kHz frequency, so we are using this to amplify.

Solution: An NMOS amplifier stage is added to **boost the amplitude** back to the desired level. We use the Active Load here as fabricating huge resistances onto circuit boards is impractical consuming large area, we use the active load(another PMOS) which occupies less space, in the simulation we realize this using a constant current source(PMOS in saturation)

How it works:

- The NMOS transistor operates in the **saturation region** to amplify the signal.
- The gate receives the filtered waveform, and the drain outputs the **amplified version**.
- Proper biasing and load resistance are chosen for linear amplification.
- We design it in the common source topology for a gain of 30 and drain current of 50uA, and a bias voltage of 0.5V, using the provided NMOS.
- we could design a better amplifier compromising over complexity

As the input impedance for the NMOS is almost infinite it does not draw a lot of current from the gate.

we also placed another high pass filter at the end just for more filtering

we notice that the final output has a difference in its bias values due to which one comes above the other, to remove this we add a bias voltage in the quadrature oscillator of 1.3mV final output of the modified circuit

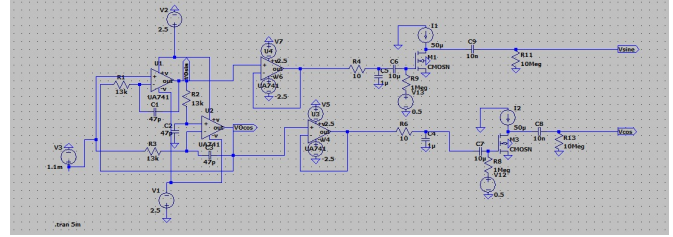


Fig. 8. final quadrature circuit

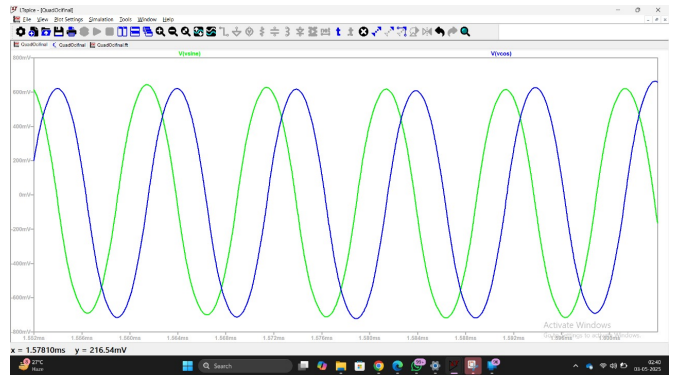


Fig. 9. final output

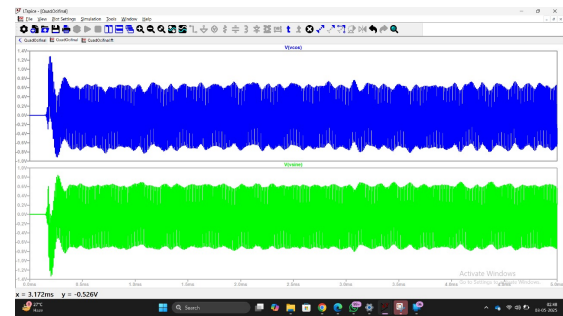


Fig. 10. final output distortions

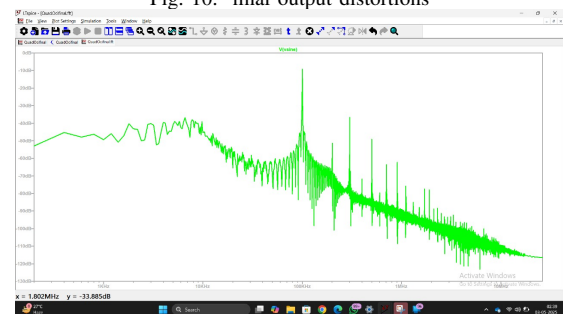


Fig. 11. FFT of output

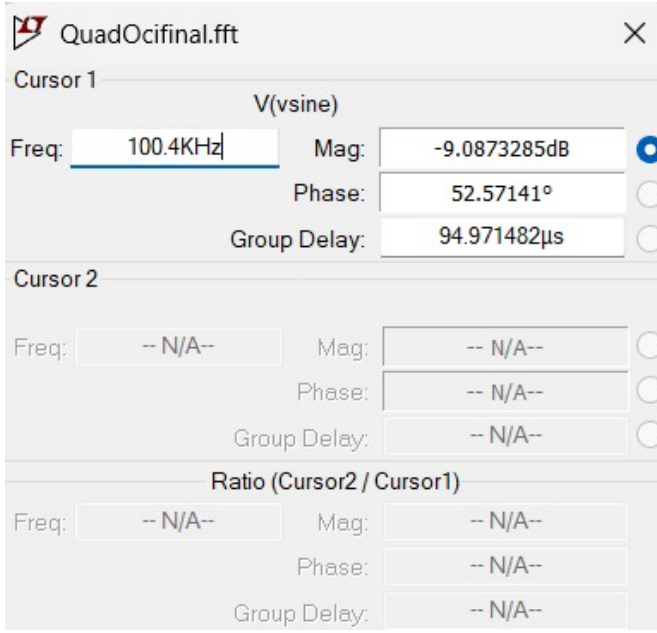


Fig. 12. frequency of output did not change, 100.4 KHz FFT

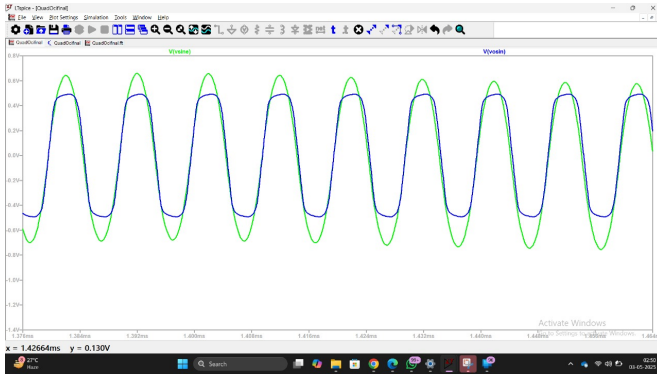


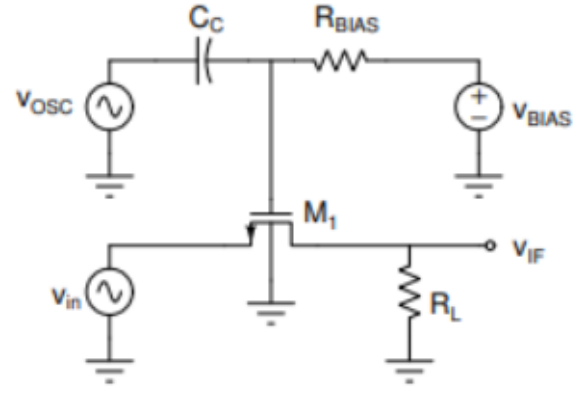
Fig. 13. comparison of initial and final output

IV. MIXER CIRCUIT

Theoretically a mixer circuit is a circuit that effectively multiplies 2 given signals, Practically realizing such a circuit is hard hence we approximate its working using non-linear devices such as MOSFET and BJT, Here we achieve this using **MOSFET** due to its lesser distortions

The Quadrature Oscillator output is given to the gate of the MOSFET, it controls the current flowing through the drain to which the input is given.

We operate the MOSFET in the linear region, as we need the output current to depend on both V_{gs} (the oscillator output) and V_{ds} (The input from the antenna)



A. Mixer Circuit Equations

$$I_D = k(V_{GS} - V_{th})(V_{DS})$$

$$R_L I_D = k(V_B + V_{OSC} - V_{out} - V_{th})(V_{in} - V_{out})$$

$$R_L X = k(V_{OSC} - R_L X)(V_{in} - R_L X)$$

$$R_L X = k(V_{OSC} - k R_L X)(V_{in} - R_L X)$$

$$R_L X = k V_{in} V_{OSC} - k V_{OSC} R_L X - k R_L V_{in} X - k R_L^2 X^2$$

$$k R_L^2 X^2 \approx 0 \quad \text{Since } X = I_D \approx 10 \mu A$$

$$X = \frac{k V_{in} V_{OSC}}{R_L + k R_L (V_{OSC} + V_{in})}$$

$$\text{Here } V_{OSC} > V_{in} > V_{out}$$

$$V_{out} = \frac{k V_{in} V_{OSC}}{1 + k (V_{OSC} + V_{in})}$$

$$\approx 10^{-3} \text{ order}$$

$$V_{out} = k V_{in} V_{OSC}$$

Finally all assumptions taken:

- $V_{Bias} \sim V_{th}$
- $I_D \sim 0$
- $k \approx 10^{-3}$ order

with these equations in our hand we take R and C values accordingly and create the Mixer Circuit.

In the Quadrature Down Converter we use both the outputs of the Quadrature Oscillator and 2 Mixer circuits

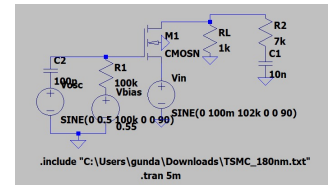


Fig. 14. Mixer circuit

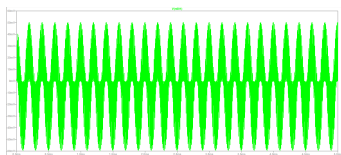


Fig. 15. Cosine for for95kHz

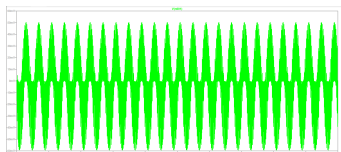


Fig. 16. Sine for for95kHz

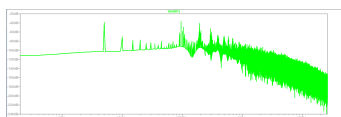


Fig. 17. FFT 95kHz

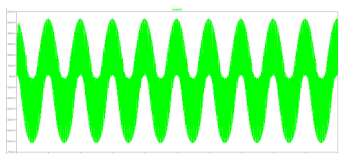


Fig. 18. Cosine for for 98kHz

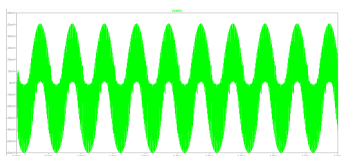


Fig. 19. Sine for for 98kHz

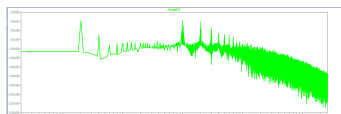


Fig. 20. FFT 98kHz

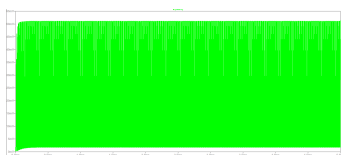


Fig. 21. Cosine for 100kHz

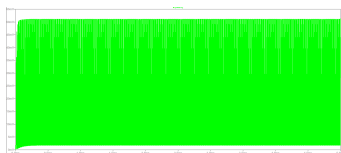


Fig. 22. Sine for 100kHz

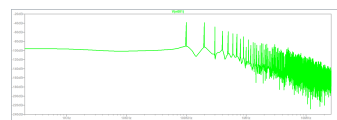


Fig. 23. FFT 100kHz

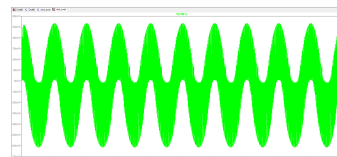


Fig. 24. Cosine for for 102kHz

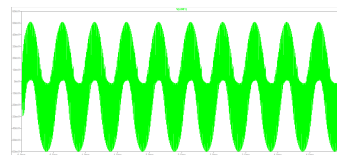


Fig. 25. Sine for for 102kHz

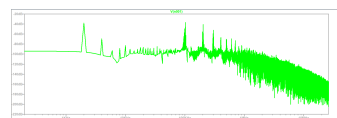


Fig. 26. FFT 102kHz

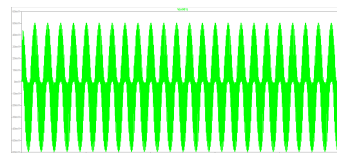


Fig. 27. Cosine for for 105kHz

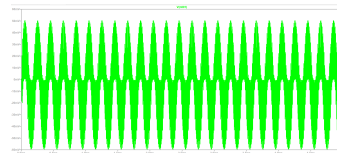


Fig. 28. Sine for for 105kHz

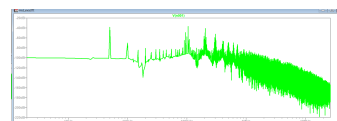


Fig. 29. FFT 105kHz

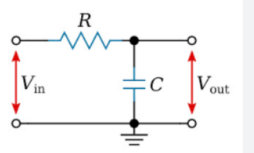


Fig. 30. RC Low pass filter

V. LOW PASS FILTER

we design a RC low pass filter with -3 dB cutoff frequency of 2KHz

A. RC Low-Pass Filter Transfer Function

Given a voltage divider circuit with a resistor R and a capacitor C , where the input voltage V_{in} is applied across the series combination and the output voltage V_{out} is taken across the capacitor:

$$Z_R = R, \quad Z_C = \frac{1}{sC}$$

Using the voltage divider rule:

$$V_{out} = V_{in} \cdot \frac{Z_C}{Z_R + Z_C}$$

Substitute the impedances:

$$V_{out} = V_{in} \cdot \frac{\frac{1}{sC}}{R + \frac{1}{sC}}$$

Multiply numerator and denominator by sC :

$$V_{out} = V_{in} \cdot \frac{1}{sRC + 1}$$

Thus, the transfer function is:

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{1}{1 + sRC}$$

now this acts as a low pass filter taking R value as 7 Kohm we get the capacitance value to be 11nF for frequency of 2KHz -3dB frequency. sending in a sine wave of frequency 1KHz(green) and 10KHz(blue) of amplitude 100mV we observe that the output comes out to be about 95mV and 20mV respectively

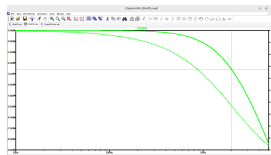


Fig. 31. RC Low pass filter

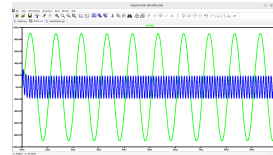


Fig. 32. output plot

VI. THE FINAL MIX

the final circuit combining all the different parts of the Quadrature Down Converter

The input signal $v_{in} = A_1 \cos(\omega_{in}t)$ is mixed with two oscillator signals: $v_{OSC_I} = A_2 \cos(\omega_{OSC}t)$ for the in-phase (I) channel and $v_{OSC_Q} = A_2 \sin(\omega_{OSC}t)$ for the quadrature-phase (Q) channel, which are 90° out of phase.

Mixing occurs through multiplication, producing IF signals v_{IF_I} and v_{IF_Q} :

- $v_{IF_I} = \frac{A_1 A_2}{2} (\cos(\omega_{in}t - \omega_{OSC}t) + \cos(\omega_{in}t + \omega_{OSC}t))$
- $v_{IF_Q} = \frac{A_1 A_2}{2} (\sin(\omega_{in}t + \omega_{OSC}t) - \sin(\omega_{in}t - \omega_{OSC}t))$
- It achieves this by multiplying the received signal with sine and cosine of the carrier frequency generated from the Quadrature Oscillator and thus produces mainly 2 sinusoids one with **frequency** $F_{in} - F_{osc}$ and **another that is** $F_{in} + F_{osc}$, then we **remove the higher frequency using the Low-Pass Filter and obtain the** $F_{in} - F_{osc}$ sinusoidal which is required.

MIXER CIRCUIT OUTPUT: I AND Q COMPONENTS

We start with the input signal:

$$x(t) = A \cos(\omega_{int}t + \phi) \quad (6)$$

This signal is mixed with:

- **In-phase oscillator:** $\cos(\omega_{osc}t)$
- **Quadrature-phase oscillator:** $\sin(\omega_{osc}t)$

In-phase (I) Component by the Mixer Circuit

$$\begin{aligned} I &= x(t) \cdot \cos(\omega_{osc}t) \\ &= A \cos(\omega_{int}t + \phi) \cdot \cos(\omega_{osc}t) \end{aligned} \quad (7)$$

Using the identity:

$$\cos A \cos B = \frac{1}{2} [\cos(A - B) + \cos(A + B)] \quad (8)$$

So,

$$I = \frac{A}{2} [\cos((\omega_{int} - \omega_{osc})t + \phi) + \cos((\omega_{int} + \omega_{osc})t + \phi)] \quad (9)$$

Quadrature (Q) Component

$$\begin{aligned} Q &= x(t) \cdot \sin(\omega_{osc}t) \\ &= A \cos(\omega_{int}t + \phi) \cdot \sin(\omega_{osc}t) \end{aligned} \quad (10)$$

Using the identity:

$$\cos A \sin B = \frac{1}{2} [\sin(A + B) - \sin(A - B)] \quad (11)$$

So,

$$Q = \frac{A}{2} [\sin((\omega_{\text{int}} + \omega_{\text{osc}})t + \phi) - \sin((\omega_{\text{int}} - \omega_{\text{osc}})t + \phi)] \quad (12)$$

Low-Pass Filter (LPF)

To extract baseband components, we **remove high-frequency terms**:

- Keep only:
 - $\cos((\omega_{\text{int}} - \omega_{\text{osc}})t + \phi)$ from I
 - $-\sin((\omega_{\text{int}} - \omega_{\text{osc}})t + \phi)$ from Q

Result:

$$I(t) = \frac{A}{2} \cos((\omega_{\text{int}} - \omega_{\text{osc}})t + \phi) \quad (13)$$

$$Q(t) = \frac{A}{2} \sin((\omega_{\text{int}} - \omega_{\text{osc}})t + \phi) \quad (14)$$

Combine I & Q into a Complex Signal:

$$I + jQ = \frac{A}{2} e^{j((\omega_{\text{int}} - \omega_{\text{osc}})t + \phi)} \quad (15)$$

This is the original baseband signal

We require both the components I and Q for the phase information to be decoded

A. Image frequencies

Consider we got an input frequency of 102KHz from the antenna, our oscillator is a bit noisy, though we have created it to generate output of 100KHz it also generates some of 104KHz, now both the frequencies generate the same output frequency of 2KHz after the Low-Pass filter, as the initial 100KHz produces the correct output(consider) then as the 104KHz produces an image frequency of the expected output frequency we call them the image frequencies

VII. THE FINAL CIRCUIT AND OUTPUTS

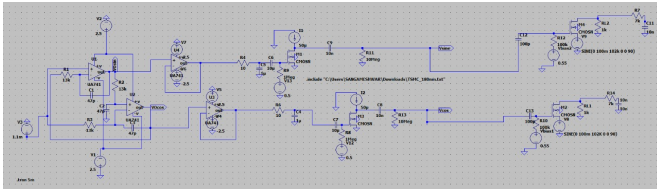


Fig. 33. Quadrature Down converter, Mixing all part

Sending In a cos wave of 102KHz as input we can see that with The quadrature oscillator producing a frequency output of 100.4 KHz we receive a output of 1.6 KHz frequency we can also see the 90 degree phase shift between both the outputs

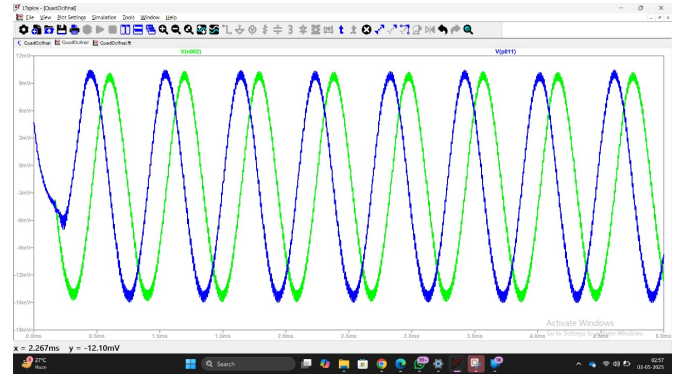


Fig. 34. final output

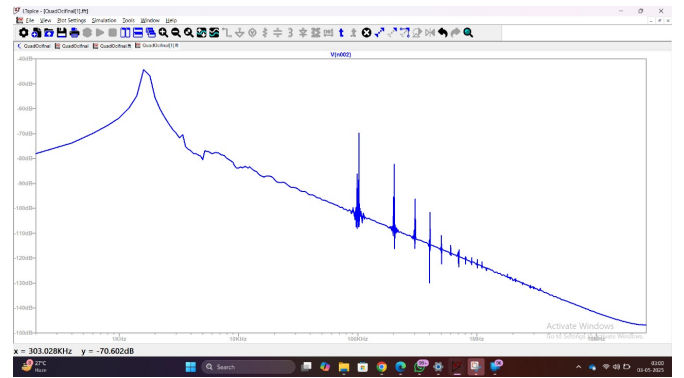


Fig. 35. Final FFT

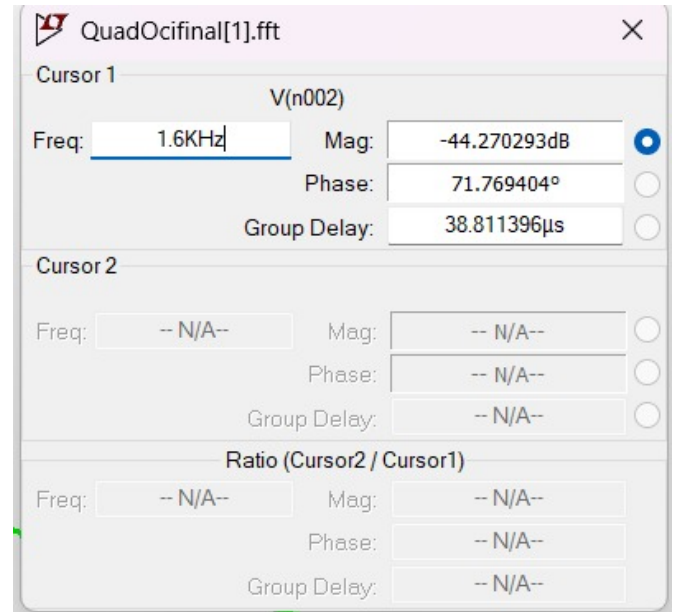


Fig. 36. FFT value 1.6KHz