Quadrature Down Converter

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***Abstract*—This paper presents a Quadrature Down Converter consisting of a quadrature oscillator, two mixers, and two low-pass filters. It generates in-phase and quadrature-phase components, tailored for use in direct conversion receivers. Quadrature down converter (QDC) is commonly used in modern day wireless receivers (RX) such as Bluetooth, Wi-Fi and WLAN. Quadrature downconversion helps in interference mitigation and improves the quality of communication.**

I. Introduction

Frequency down converters are integrated assemblies that covert a high frequency RF (Radio Frequency) to a low frequency IF(Intermediate Frequency).

This is done because channel-selection filtering is extremely difficult at higher frequencies, and handling lower frequencies are easier to process.

Down Conversion is done by mixing the incoming signal with signals from the local oscillator to shift its frequency, filtering out higher frequencies through a low pass filter and keeping the lower frequencies to extract information post modulation.

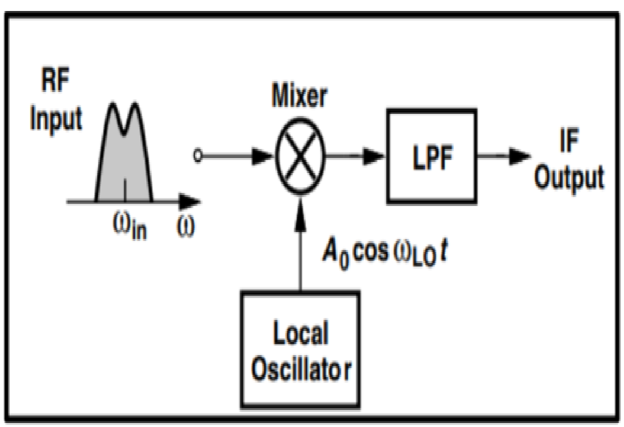


Fig.1 Block diagram of Down Conversion

After mixing the input signal $A\cos(\omega_{\text{in}})$ with the signals from the local oscillator we obtain signals with frequencies $\pm(\omega_{\text{in}} \pm \omega_{\text{LO}})$.

From this we want to filter out the $\pm(\omega_{\text{in}}+\omega_{\text{LO}})$ frequencies (RF), and keep only the $\pm(\omega_{\text{in}}-\omega_{\text{LO}})$ (IF). This is done using the lowpass filter.

The above mentioned process is called "down conversion".

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

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

From equations (1) and (2) we see that regardless of whether ω_{in} is greater than or lesser than ω_{LO} it gets down converted to the same IF. In other words two spectra located symmetrically around ω_{LO} will get down converted to the same IF. Because of this symmetry the component at ω_{im} is called the image of the desired signal.

$$\omega_{\text{im}} = \omega_{\text{in}} + 2\omega_{\text{IF}} = 2\omega_{\text{LO}} - \omega_{\text{in}}$$

There are numerous instances where the received signal may be interrupted by other users(Ex. Wi-Fi). If one of these interferences is say $2\omega_{\text{LO}} - 2\omega_{\text{in}}$, in this instance the signal is corrupted after down conversion and the proper information cannot be extracted.

Down conversion of an asymmetrically modulated signal to a zero IF leads to self-corruption unless the base-band signals are separated by their phases. Hence, a Quadrature Down converter is a solution to solving this problem. In quadrature down conversion, two versions of the down converter signal are created with a phase difference of 90°.

In a quadrature down converter the input signal is mixed with two signals one a cosine wave and one a sine wave. Thus the same RF data will go into two different paths and we get in-phase and quadrature phase signals which have a mutual phase difference of 90°. This seperation allows them to 1.Distinguish overlapping signals, 2. Reject interference 3. Preserve information in asymetric conditions.

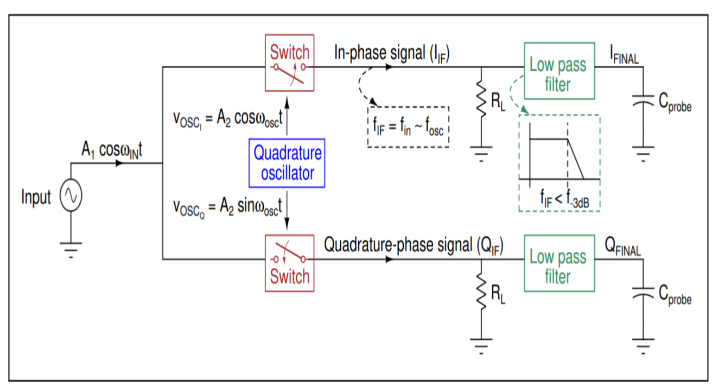


Fig.2 Quadrature Down Converter.

The input signal $v_{\text{in}} = A_1 \cos(\omega_{\text{in}} t)$ is mixed with $v_{\text{oscI}} = A_2 \cos(\omega_{\text{osc}} t)$ and $v_{\text{oscQ}} = A_2 \sin(\omega_{\text{osc}} t)$ to produce in-phase (v_{IF_I}) and quadrature-phase (v_{IF_Q}) intermediate frequency (IF) signals respectively.

Mixing of two signals is equivalent to their multipliation as seen below.

$$v_{\text{IF}_I} = v_{\text{in}} \cdot v_{\text{oscI}} = \frac{A_1 A_2}{2} \left[\cos(\omega_{\text{in}} t - \omega_{\text{osc}} t) + \cos(\omega_{\text{in}} t + \omega_{\text{osc}} t)\right] \tag{3}$$

$$v_{\text{IF}_Q} = v_{\text{in}} \cdot v_{\text{oscQ}} = \frac{A_1 A_2}{2} \left[\sin(\omega_{\text{in}} t + \omega_{\text{osc}} t) - \sin(\omega_{\text{in}} t - \omega_{\text{osc}} t)\right] \tag{4}$$

The mixed signal is fed to a low pass filter and only the IF signals with frequency $\omega_{\text{IF}=(\omega_{\text{in}}} - \omega_{\text{OSC}})$ are passed, which can be a sufficiently low value for a sufficiently high value of ω_{in} and ω_{OSC}.

We now look into the components of the Quadrature Down Converter.

II. Quadrature Oscillator

An oscillator is a form of frequency generator that can generate a sinusoidal wave with constant frequency and amplitude. Oscillator circuits produce specific periodic waveforms such as square, triangular, saw-tooth, and sinusoidal. Quadrature is another type of phase-shift sinusoidal oscillator. Quadrature generators produce two sinusoidal signals of identical frequency and amplitude but of different phase angles. A rectangular quadrature signal has a phase shift of 90°.

A. Criteria for Oscillation

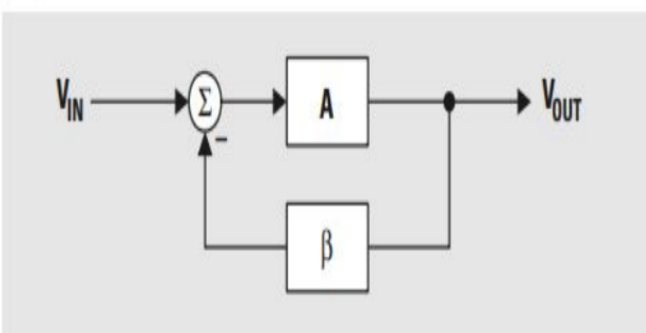


Fig.3 A traditional feedback system

The figure above shows a traditional feedback system, we can present the performance of the system as:

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

We notice that when $A\beta = -1$, the system becomes unstable and V_{out} goes to infinity(theoretically).

Aβ becomes -1 when Aβ = 1∠–180°, i.e. a phase shift of 180°.

As the phase shift approaches 180° and $|A\beta| \to 1$, the output voltage of the now unstable system tends to infinity but is limited by the power supply. The value of A changes and forces $A\beta$ away from the singularity as the output voltage approaches either of the power rail.

Thus, the trajectory towards an infinite voltage slows and eventually halts. The system stays linear and reverses direction, heading to the opposite power rail. This produces a sine wave oscillator.

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

Furthermore, the op-amp's slew rate limitation must be taken into consideration. The slew rate must be greater than $2\pi V_P f_o$, where V_P is the peak voltage and f_o is the oscillation frequency. Otherwise, distortion of the output signal occurs.

B. Achieving Phase Shift

The 180° phase shift in the equation $A\beta = 1\angle - 180°$ is introduced by active and passive components. Oscillators are made dependent on passive component phase shift because it is accurate and almost drift-free.

The phase shift contributed by active components is minimized because it varies with temperature, has a wide initial tolerance, and is device independent. Amplifiers are selected such that they contribute little or no phase shift at the oscillation frequency.

A single-pole RL or RC circuit contributes up to 90° phase shift per pole, and because 180° is required for oscillation, at least two poles must be used in oscillator design.

An LC circuit has two poles; thus, it contributes up to 180° phase shift per pole pair, but LC and LR oscillators are not considered here because low-frequency inductors are expensive, heavy, bulky, and non-ideal.

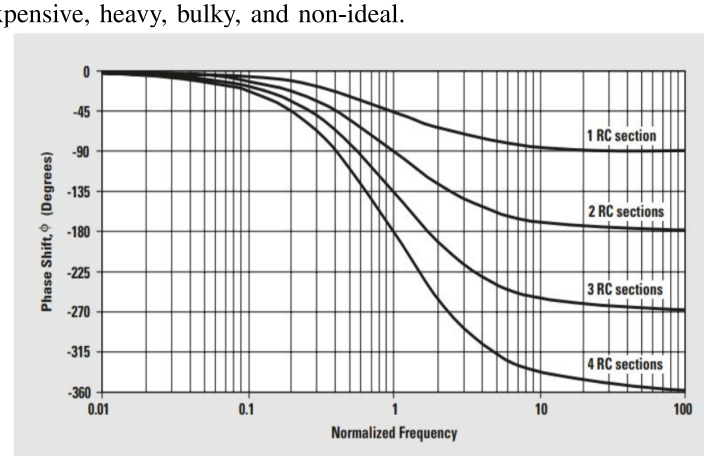


Fig.4 Phase plot of RC Sections

C. Working of Quadrature Oscillator

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

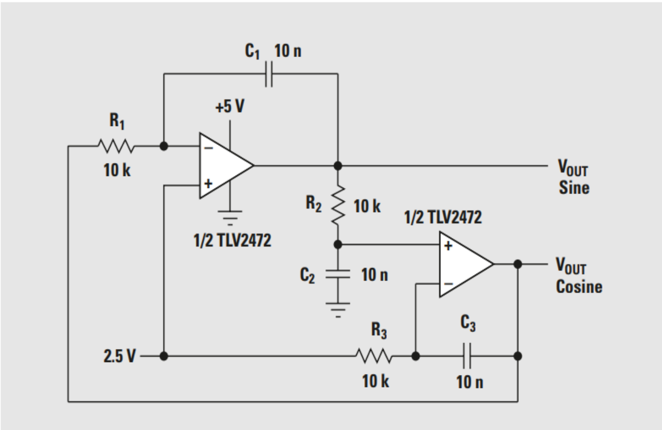


Fig.5 Circuit Diagram of Quadrature Oscillator

The three RC sections are configured so that each section contributes 90° of phase shift. The outputs are labeled sine and cosine (quadrature) because there is a 90° phase shift between op-amp outputs. The loop gain is calculated as:

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

If $R_1C_1 = R_2C_2 = R_3C_3$ the equation simplifies to:

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

When $\omega = \frac{1}{RC}$, the above equation reduces to $1\angle -180°$, so oscillation occurs at $\omega = 2\pi f = \frac{1}{RC}$.

Adjusting the gain can increase the amplitudes. But as a trade-off, we would have reduced bandwidth.

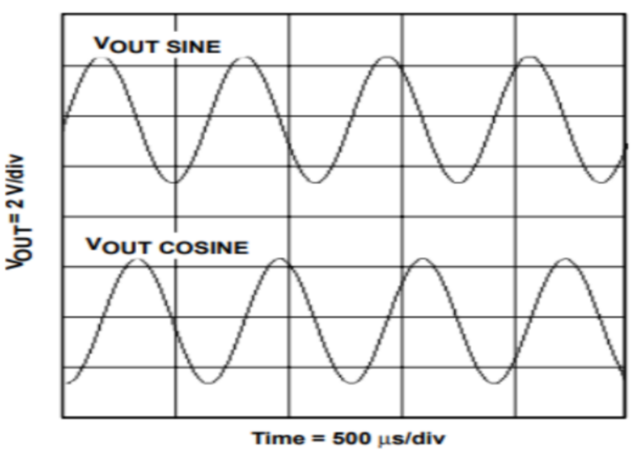


Fig.6 Expected Output of Quadrature Oscillator

D. Requirements for Quadrature Oscillator

1) Amplitude of generated waves = 3 V_{pp}
2) Frequency of generated waves = 69 kHz
3) Phase difference between generated waves is 90°.

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

1) $R_1 = R_2 = R_3 = 1.6k$
2) $C_1 = C_2 = C_3 = 1nF$
3) $V_{DD} = +5V$ and $V_{SS} = 0V$
4) Op-Amp chosen is UA-741.

E. LT-Spice simulation of circuit:

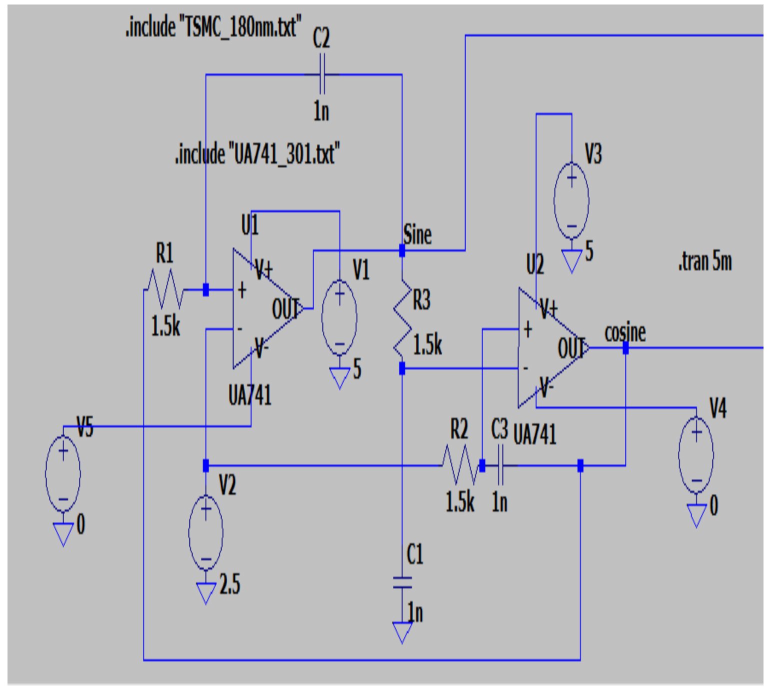


Fig. 7 LT-Spice simulation of circuit

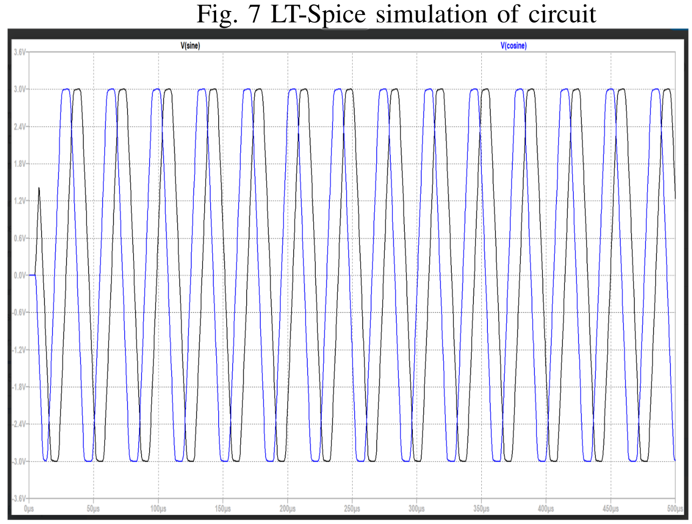
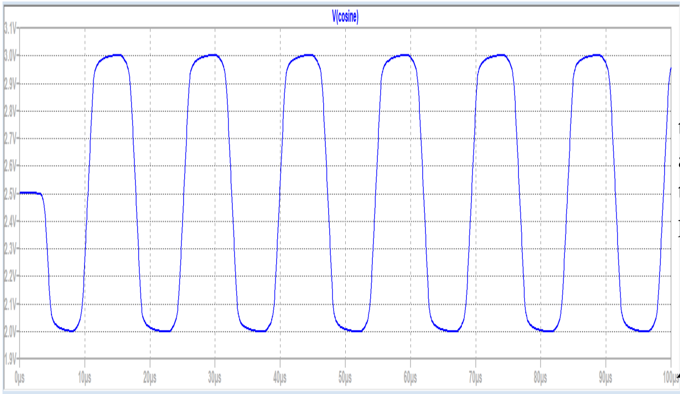
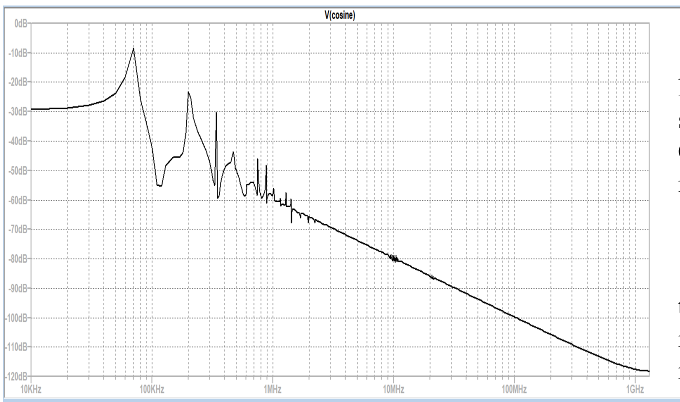


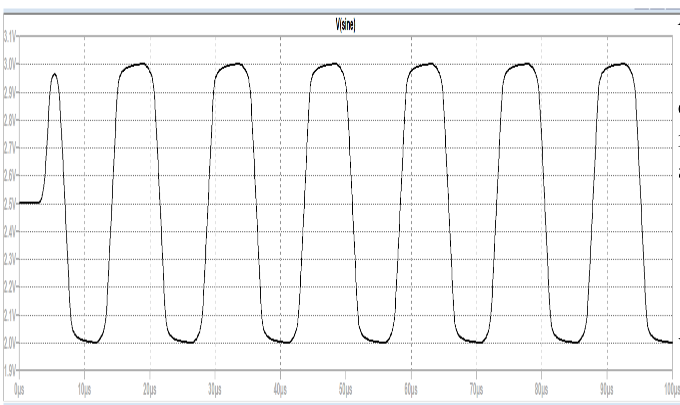
Fig 8. Output of two waves, phase difference = 90°



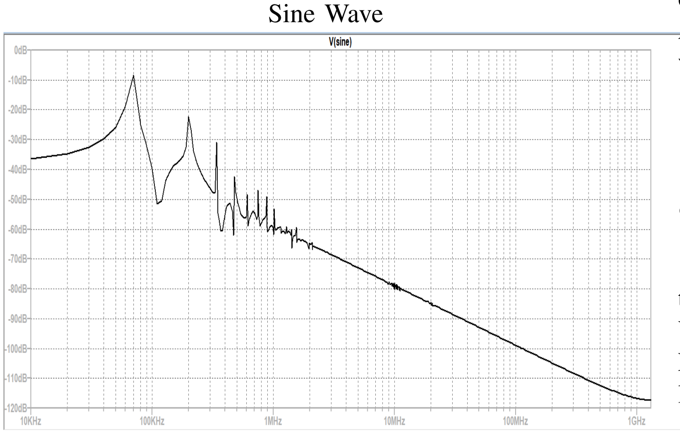
Cos Wave



Cos Wave fft



Sine Wave



Sine Wave fft

III. SWITCH(MIXER)

A signal mixer is a device or circuit used to combine two or more input signals into a single output signal. Mixers are commonly used in various fields of electronics, including telecommunications, radio frequency (RF) engineering, audio, processing, and instrumentation.

A. *Design Considerations*

Typical conditions for a Switch to be Ideal:

• The Duty Cycle of the Switch should be 50

• The internal resistance of the Switch should be very less(Approximately zero).We can realize the switch using a simple MOSFET, where theoscillator signal is applied to the Gate of the device, Input isapplied at the source and the intermediate frequency output istaken at the Drain end.

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B. *Acheiving very low internal resistance*

A MOSFET can operate as a resistor value which is controlled by the overdrive voltage (V_{GS} - V_{TH}) when it is in Deep Triode Region. This Resistance can be represented as:

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

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

The Technological parameters like μ_n, C_{ox}, V_{TH} are not in our hand. So, the only way this can be done is by increasing the Aspect Ratio W/L. We observe that the loss is greatly reduced when we decreased the value of Length of the MOSFET.

C. *Achieving 50% Duty Cycle*

To attain a 50% duty cycle we need to Bias the Gate terminal at the Threshold Voltage. When Gate-Source Voltage, V_{GS} , is greater than the Threshold Voltage, V_{TH} then the NMOS is in Linear Mode and thus conducting and when it is less it won't conduct.

Thus, to get 50% Duty Cycle, V_G, i.e., Vosc should operate across V_{TH}.

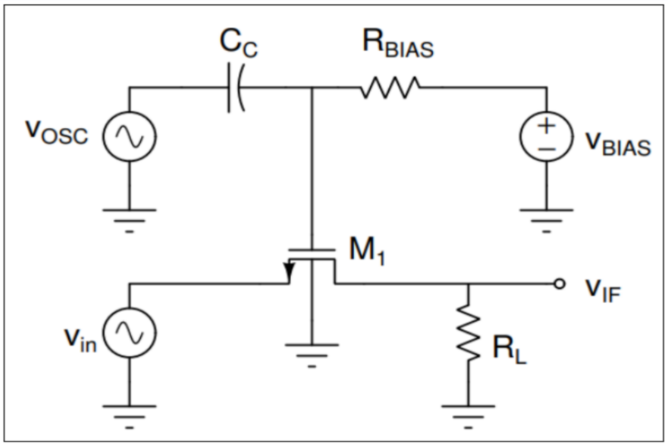


Fig. 9 Circuit Diagram of Mixer

D. Biasing the gate terminal

AC and DC sources cannot directly be connected, because when AC Signal is flowing, it will seek a very low impedance connected to Ground (as the internal resistance of an Ideal Source is very small) compared to the high Impedance at the Gate terminal. So, whole AC Current will flow through the DC Source, as it will follow the low impedance path.

To prevent the flow of DC current to the AC source a capacitor C_{BIAS} is added 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. C_{BIAS} is chosen to be 1.7µ.

To prevent the flow of AC Current to the DC Source a Resistor, R_{BIAS}, of very high resistance is added next to the DC source to increase the impedance. Thus, preventing the AC current to flow through the DC source. Any high value for the resistance can be chosen. We chose R_{BIAS} = 100k.

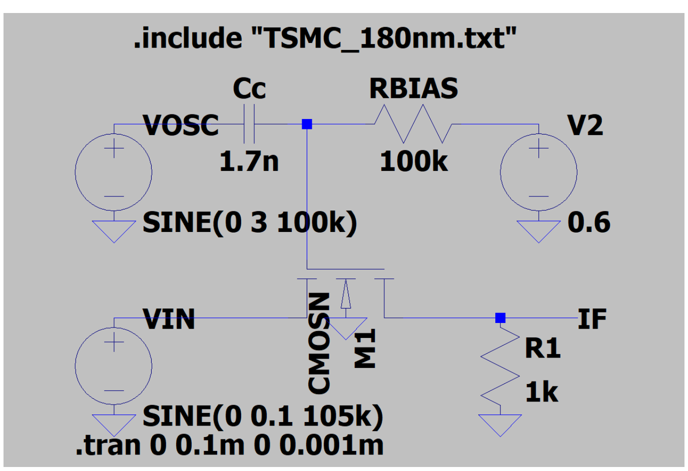
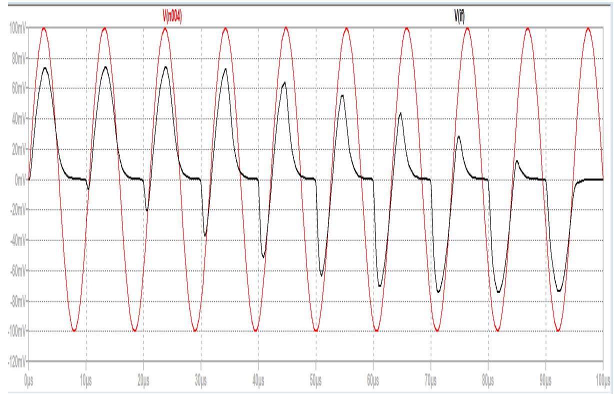
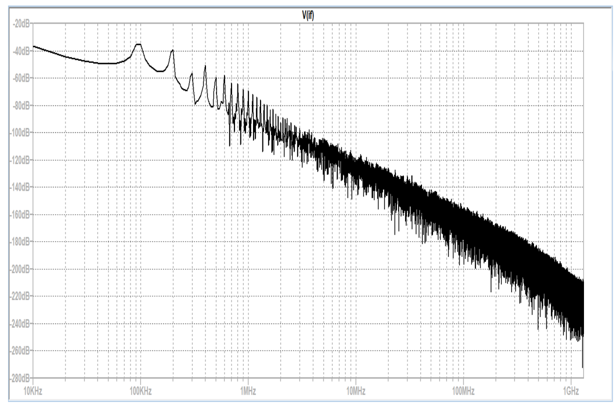


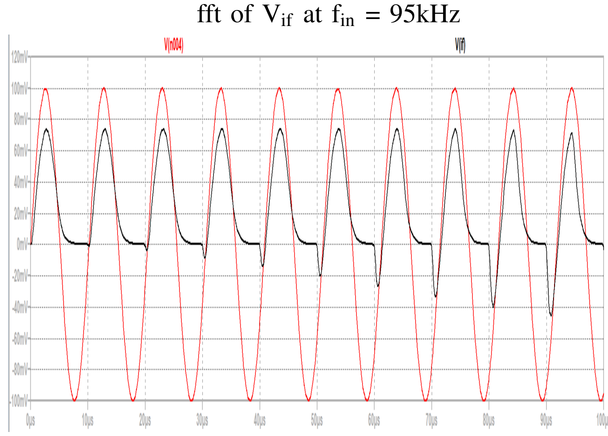
Fig. 10 LT-Spice simulation of circuit



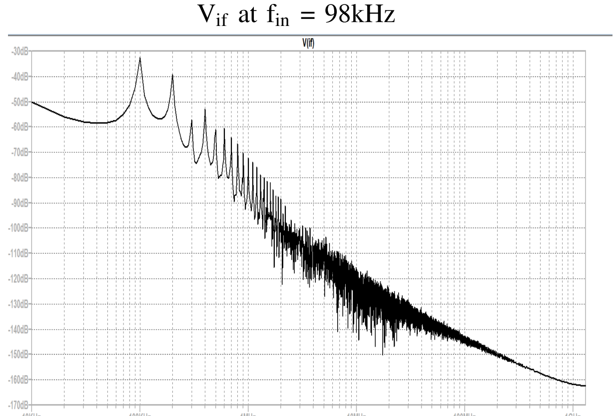
V_{if} at f_{in} = 95kHz



fft of V_{if} at f_{in} = 95kHz



V_{if} at f_{in} = 98kHz

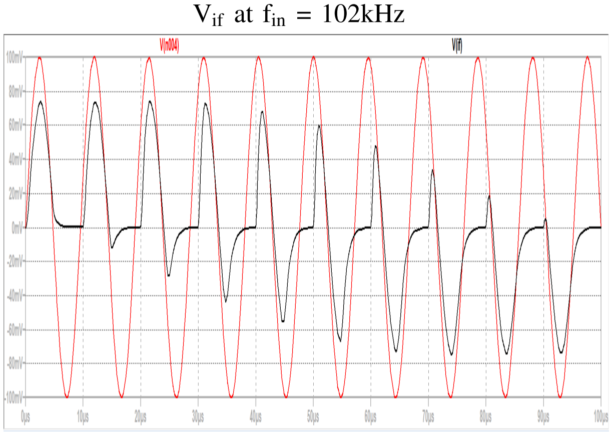


fft of V_{if} at f_{in} = 98kHz

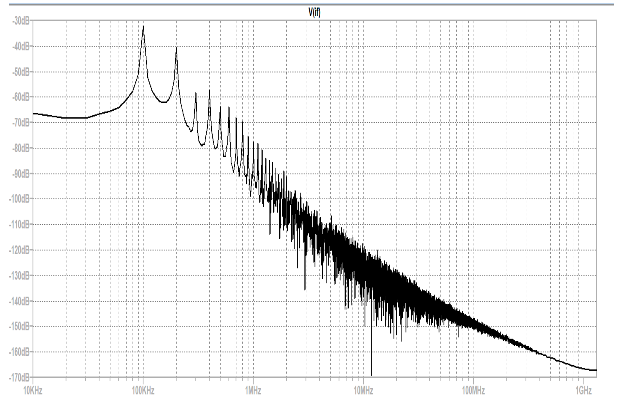
V_{if} at f_{in} = 99kHz

V_{if} at f_{in} = 101kHz

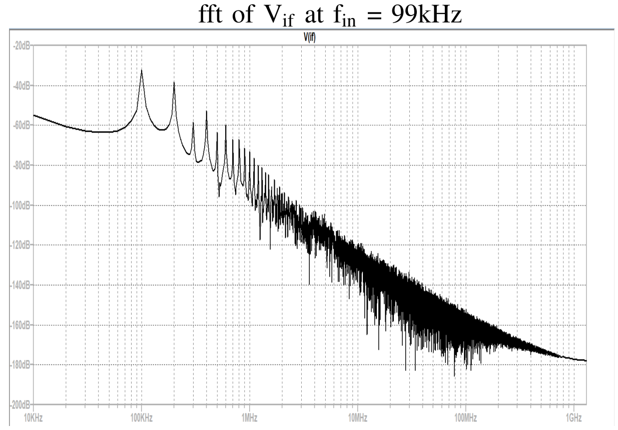
V_{if} at f_{in} = 102kHz



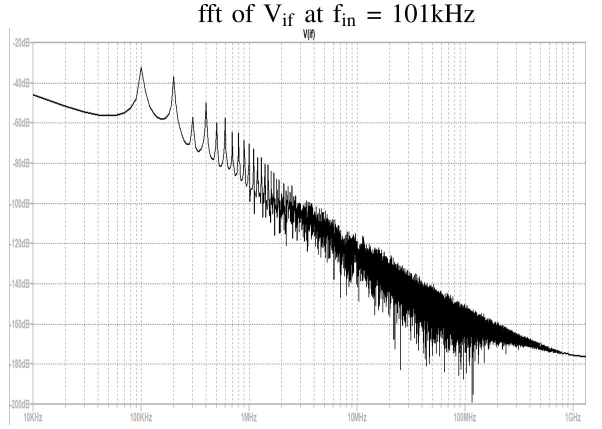
V_{if} at f_{in} = 105kHz



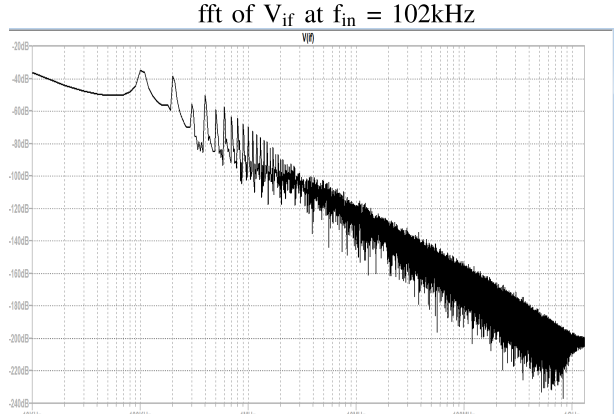
fft of V_{if} at f_{in} = 99kHz



fft of V_{if} at f_{in} = 101kHz



fft of V_{if} at f_{in} = 102kHz



fft of V_{if} at f_{in} = 105kHz

IV. Low-Pass Filter

A Low Pass Filter is an electronic circuit that allows low-frequency signals to pass while attenuating high-frequency signals above a specified cut-off frequency.

For applications up to 69kHz, passive low pass filters typically use RC (Resistor-Capacitor) networks, while higher frequency designs may incorporate RLC (Resistor-Inductor-Capacitor) components. These passive filters consist only of resistors, capacitors, and inductors, offer no signal amplification and thus the output signal is always lesser than the input signal.

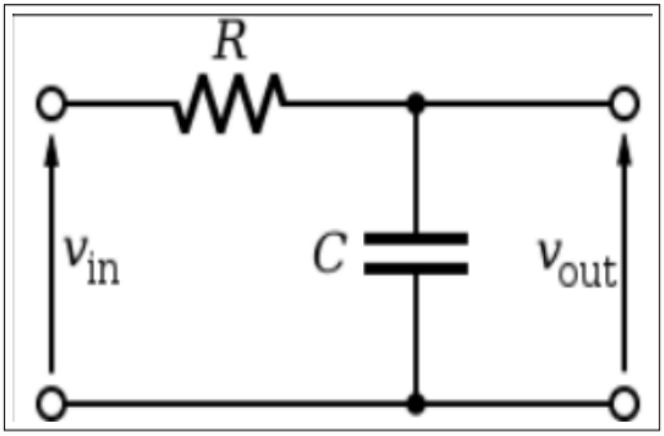


Fig. 11 An RC Low-Pass Filter

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.

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.

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

$$V_C = V_{\text{IN}} \cdot \frac{X_C}{R + X_C}$$

$$V_C = V_{\text{IN}} \cdot \frac{1}{1 + 2\pi fRC} \tag{5}$$

$$V_R = V_{\text{IN}} \cdot \frac{R}{R + X_C}$$

$$V_C = V_{\text{IN}} \cdot \frac{2\pi fRC}{1 + 2\pi fRC} \tag{6}$$

As we can observe from equation (5) 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.

However, as we can see from equation (6) at high frequencies the capacitive reactance (XC) is much lesser 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.

A. Design and specifications

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

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

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

$$RC = 7957 \times 10^{-8} \tag{2}$$

So we choose:
1) R = 7957Ω
2)C = 10n
3)f_c = 2000.1877Hz

B. LT-Spice Simulation

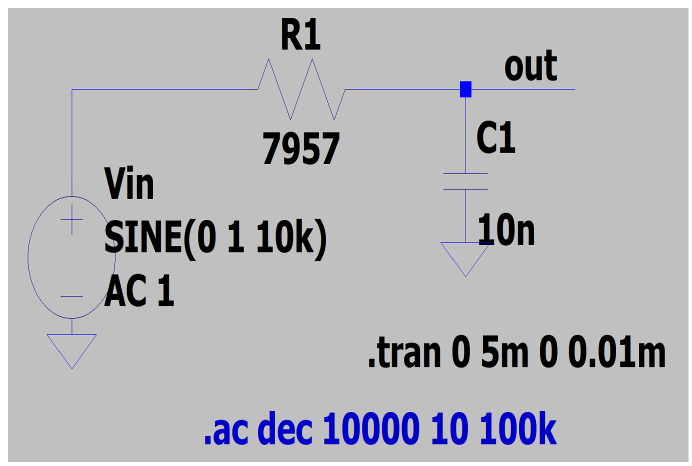


Fig. 12 LT-Spice Simulation of lowpass filter circuit

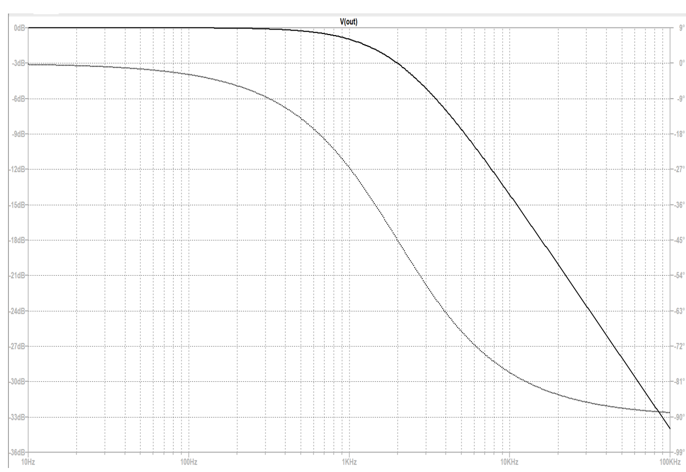
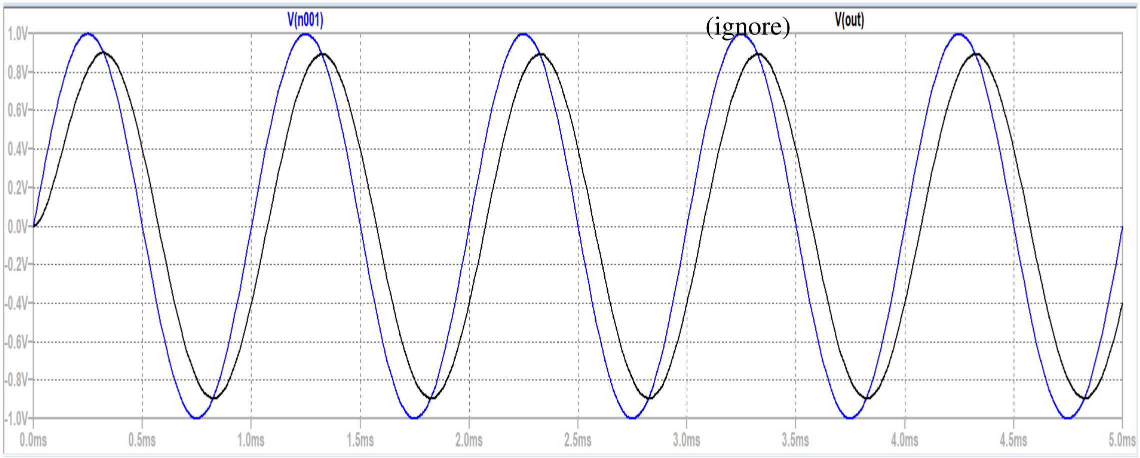
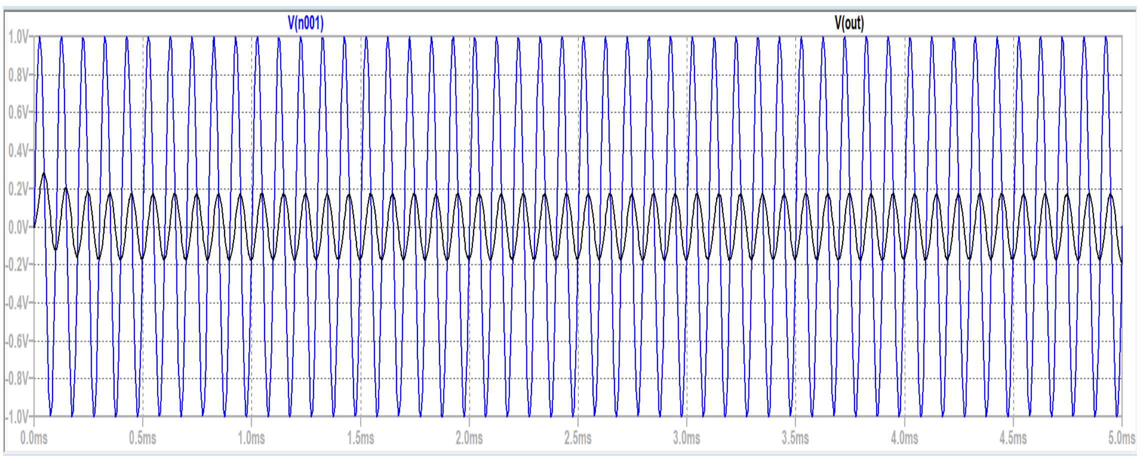


Fig. 13 Frequency Response of LPF



Response at 1kHz



Response at 10kHz

V. Complete Circuit

Connecting all the building blocks – Oscillator, Mixer and Filter, the final circuit is implemented.

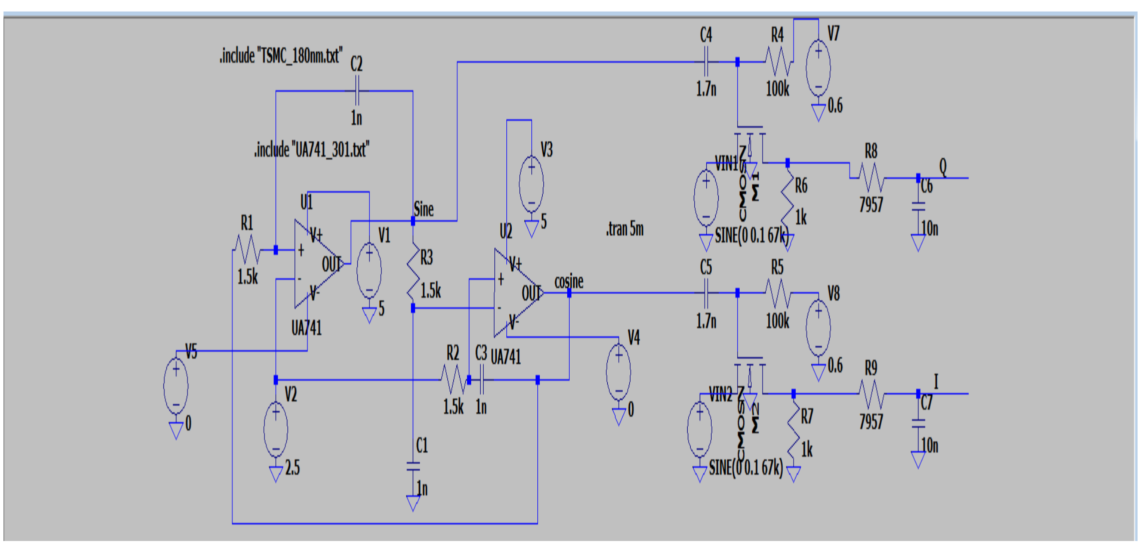
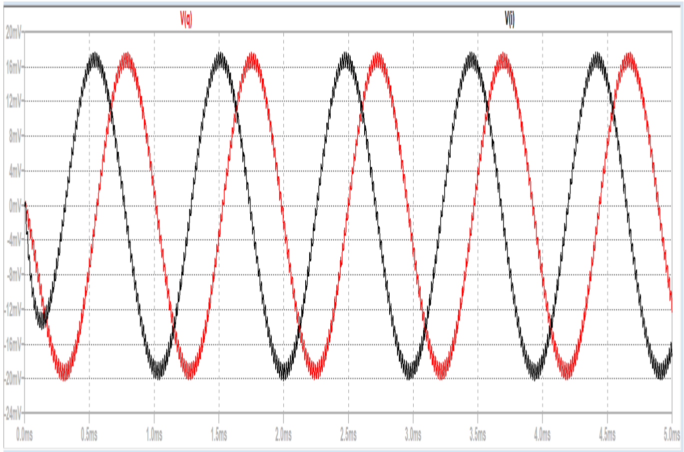
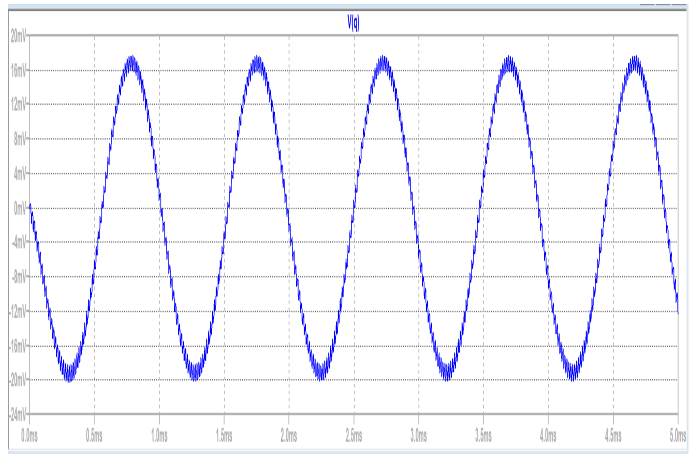


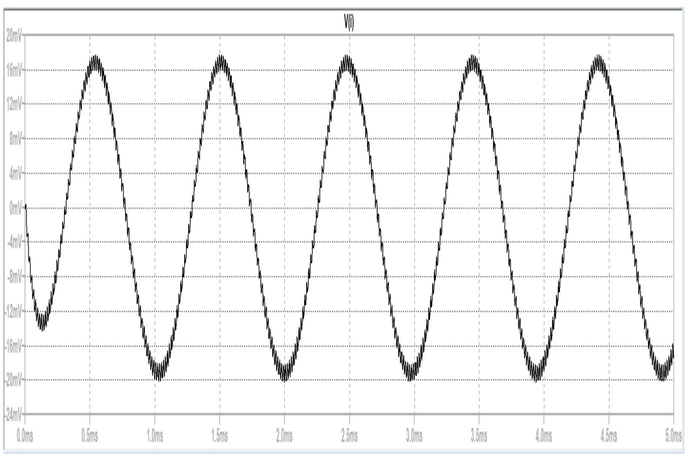
Fig 14. Full Circuit Implementation



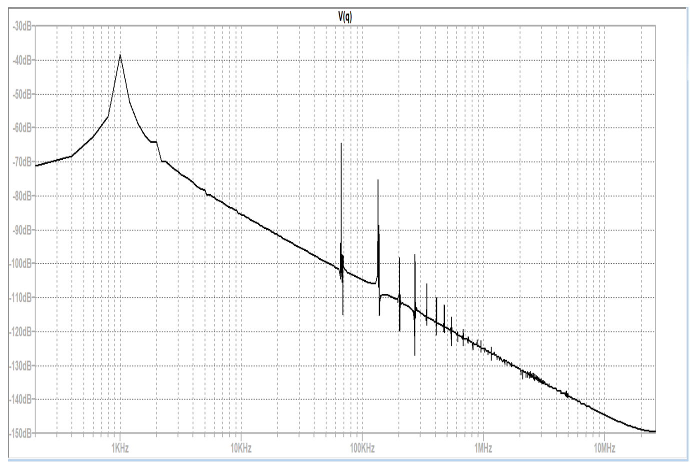
Output of Topology



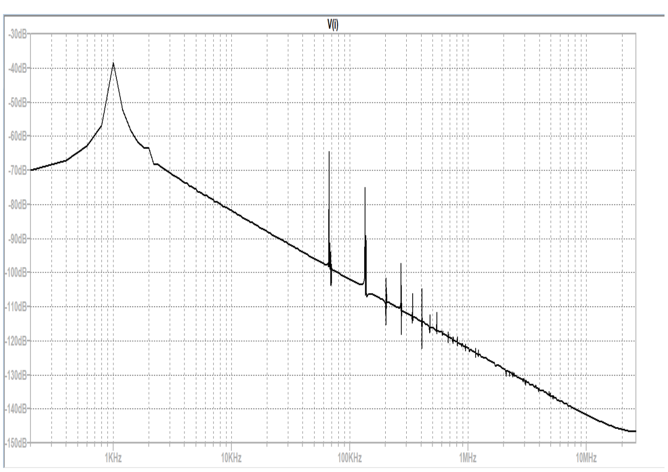
Quadrature Phase Output of Topology



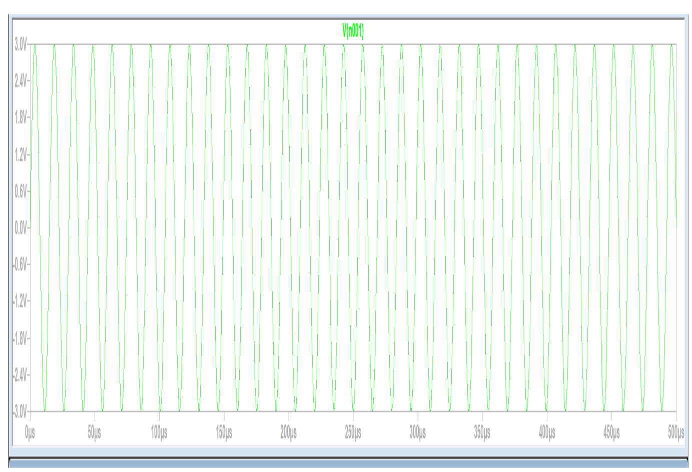
In-Phase Output of Topology



FFT of Quadrature Phase Output



FFT of In-Phase Output



Input Signal

A. Final Results

We observe that the first peak in the FFT plot is at 2 kHz. The input signal has a frequency of 67 kHz, and the waves generated by the oscillator have a frequency of 69 kHz. When these waves are mixed and passed through the low-pass filter, only the component of the signal with a frequency less than the cutoff frequency gets passed, i.e., the wave with frequency $f_{\text{osc}} - f_{\text{in}}$.

Parameters	**Simulated**	**Calculated**
Oscillator Frequency	68 kHz	100 kHz
Oscillator Amplitude (I-phase)	17.6 mV	0.1 V
Oscillator Amplitude (Q-phase)	17.6 mV	0.1 V
Input Frequency	66 kHz	98 kHz
IF	2 kHz	2 kHz
Supply	2.5 V	2.5 V
VBIAS	600 mV	560 mV
Cc	1.7 nF	1.7 µF
RBIAS	100 kΩ	100 kΩ
R1, R2, R3	1.5 kΩ	1.5 kΩ
C1, C2, C3	1 nF	1 nF

TABLE I: Comparison of simulated and calculated parameters

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