Course Project - Analog Electronic Circuits

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

I. Introduction

Frequency Down converters are integrated assemblies that convert a high-frequency RF (Radio frequency) signal to a lower frequency IF (Intermediate Frequency) signal.

Channel-selection filtering proves very difficult at high carrier frequencies. The translation is performed by means of a "mixer".

To lower the centre frequency, the signal is multiplied by a sinusoid $A_0cos(\omega L_{L0}t)$, which is generated by a local oscillator (LO). Since multiplication in the time domain corresponds to convolution in the frequency domain, the impulses at $\pm\omega_{L0}$ shifts the desired channel to $\pm(\omega_{in} \pm \omega_{L0})$.

The components at $\pm(\omega_{in} + \omega_{LO})$ are not of interest and are removed by the low-pass filter (LPF), leaving the signal at a centre frequency of $(\omega_{in} - \omega_{LO})$. This operation is called "down conversion."

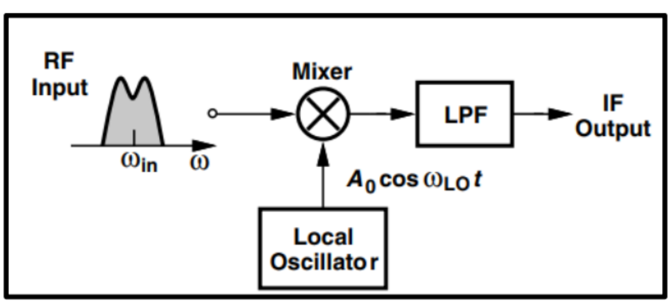


Fig. 1. Block Diagram of Down Conversion

$$Acos(\omega_{IF}t) = Acos(\omega_{in} - \omega_{L0}) \tag{1}$$

$$Acos(\omega_{IF}t) = Acos(\omega_{L0} - \omega_{in}) \tag{2}$$

From the equations (1) and (2) it can be observed that irrespective of whether ω_{in} lies above ω_{LO} or below ω_{LO}, the input translates to the same IF. In other words, two spectra located symmetrically around ω_{LO} are down converted to the same IF. Due to this symmetry, the component at ω_{im} is called the image of the desired signal.

$$\omega_{im} = \omega_{in} + 2\omega_{IF} = 2\omega_{LO} - \omega_{in} \tag{3}$$

There are numerous users in all standards (from police to WLAN bands) that transmit signals and produce many interference. If one interference happens to fall at $\omega_{im} = 2\omega_{LO} - 2\omega_{in}$, then it corrupts the desired signal after down conversion.

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°.

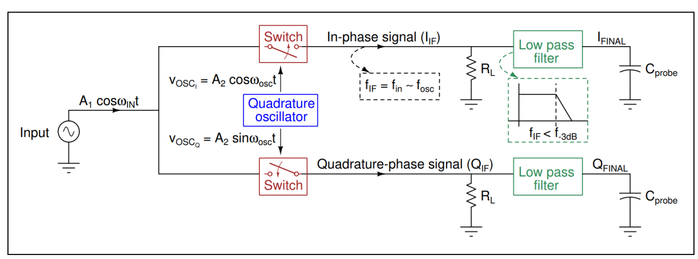


Fig. 2. Quadrature Down Converter

This quadrature down conversion uses two mixers, one fed with a cosine wave and the other with sine wave. So, the same RF data will go to two different paths to be changed to quadrature signals. These signals are in base-band, hence denoted by BB.

The input signal $v_{in} = A_1cos(\omega_{in}t)$ is mixed with $v_{osc_I} = A_2cos(\omega_{osc}t)$ and $v_{osc_Q} = A_2sin(\omega_{osc}t)$ to produce in-phase (v_{IF_I}) and quadrature-phase (v_{IF_Q}) intermediate frequency (IF) signals, respectively.

The in-phase and quadrature-phase signals have a phase difference of 90°. Mixing of two signals is equivalent to their multiplication.

$$v_{IF_I} = v_{in} v_{osc_I} = \frac{A_1 A_2}{2}(cos(\omega_{in}t - \omega_{osc}t) + cos(\omega_{in}t + \omega_{osc}t) \quad (4)$$

$$v_{IF_Q} = v_{in} v_{osc_Q} = \frac{A_1 A_2}{2}(sin(\omega_{in}t + \omega_{osc}t) - sin(\omega_{in}t + \omega_{osc}t) \quad (5)$$

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

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 wave-forms such as square, triangular, saw-tooth, and sinusoidal. There are two main classes of oscillator - relaxation and sinusoidal. The relaxation oscillator generates triangular, saw-tooth, and other non-sinusoidal wave-forms. 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 90^o phase shift.

A. Design Considerations

Two integrator stages are connected in series with an inverter, of which the output is feedback to the input of the first stage.

Op-Amp oscillators are used. These are circuits that are designed intentionally to remain in an unstable or oscillatory state. Op-Amp sine wave oscillators operate without an externally applied input signal. A combination of positive and negative feedback is used to drive the Op-Amp into an unstable state, causing the output to cycle back and forth between the supply rails at a continuous rate. The frequency and amplitude of oscillation are set by the arrangement of passive and active components around a central Op-Amp.

B. Conditions for Oscillation

Oscillators do not need an externally applied input signal, instead, they use some fraction of the output signal created by the feedback network as the input signal.

$$V_{IN} = V_{OUT}(\frac{1}{A} + \beta) \quad (6)$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \quad (7)$$

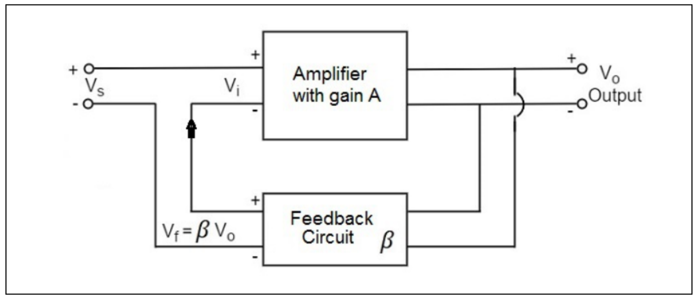


Fig. 3. Feedback Oscillator Circuit

- Oscillation results when the feedback system is not able to find a stable steady-state because its transfer function cannot be satisfied. The system becomes unstable when $1 + A\beta = 0$ or $A\beta = -1$
- Moreover, the magnitude of loop gain must be unity with a corresponding phase shift of 180^o

These conditions are called ***The Barkhausen Criterion***

As the phase shift approaches 180^o and $|A\beta| \rightarrow 1$, the output voltage of the now unstable system tends to infinity but, it is limited to finite values by an energy-limited power supply. The value of A changes and forces $A\beta$ 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.

The op-amp must be chosen with correct bandwidth or else the output will oscillate at a frequency below the design specification.

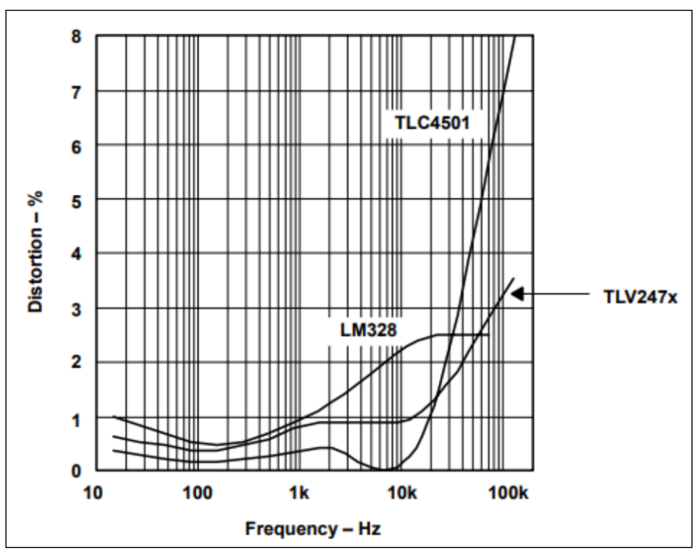


Fig. 4. Distortion vs Oscillation Frequency for Various Op-Amp Bandwidths

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

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

C. Working of a Quadrature Oscillator

In a quadrature oscillator, the original sine wave is 180^o 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.

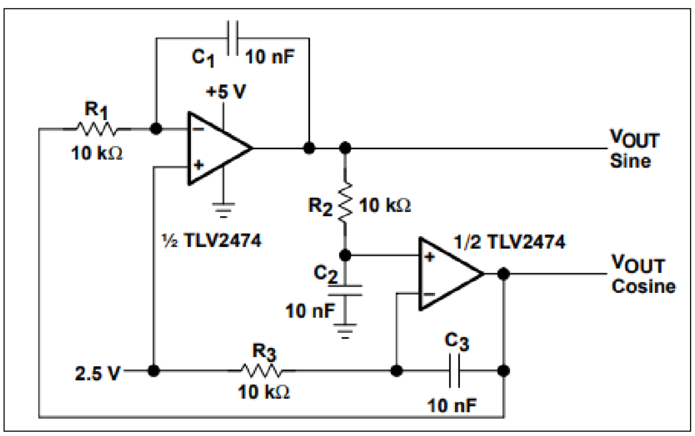


Fig. 5. Circuit Diagram of Quadrature Oscillator

The loop gain is calculated from the following equation -

$$A\beta = A\left(\frac{1}{R_1C_1s}\right)\left[\frac{R_3C_3s+1}{R_3C_3s(R_2C_2s+1)}\right] \tag{8}$$

If $R_1C_1 = R_2C_2 = R_3C_3 = RC$, the equation simplifies to,

$$A\beta = A\Big(\frac{1}{RCs}\Big)^2 \tag{9}$$

When $\omega = \frac{1}{RC}$, the equation reduces to $1\angle-180^o$, so oscillations occur 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.

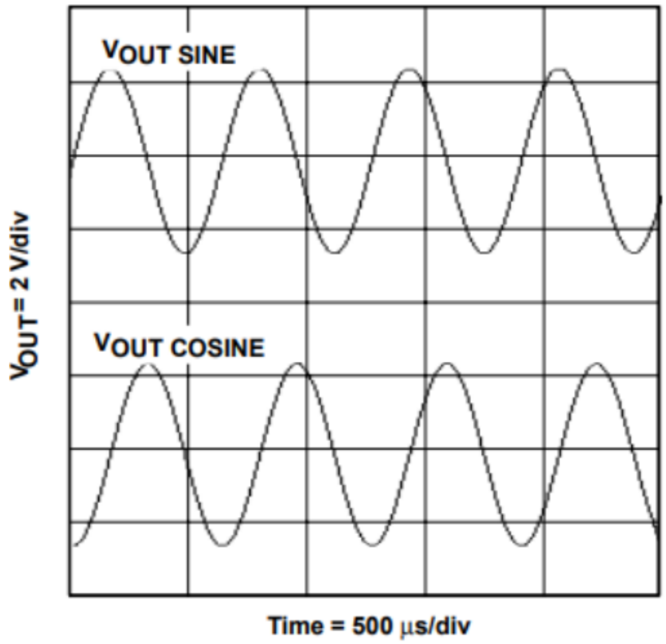


Fig. 6. Expected Output of Quadrature Oscillator

D. Requirements for the Quadrature Oscillator

- Amplitude of the generated waves = 1 V_{pp}
- Frequency of the generated waves = 100 kHz
- Phase difference between the waves = 90^o

Phase Difference is calculated as -

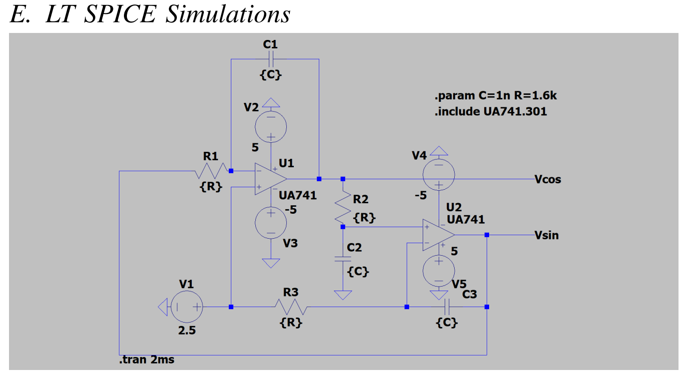
$$\Phi = tan^{-1}(-\omega RC) - tan^{-1}(\frac{1}{\omega RC}) + \frac{\pi}{2} \tag{10}$$

$\Phi = \pi/2$ when $\omega = 1/RC$.

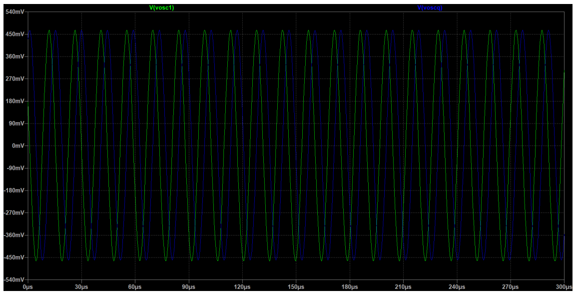
In accordance with the design requirements, the following values have been taken for the quadrature oscillator:

1) $R_1 = R_2 = R_3 = R = 1.5k\Omega$
2) $C_1 = C_2 = C_3 = C = 1nF$
3) V_{DD} = +5V and V_{SS} = -5V
4) $\frac{1}{RC} = 0.67 \times 10^6$
5) Op-Amp Chosen = UA-741

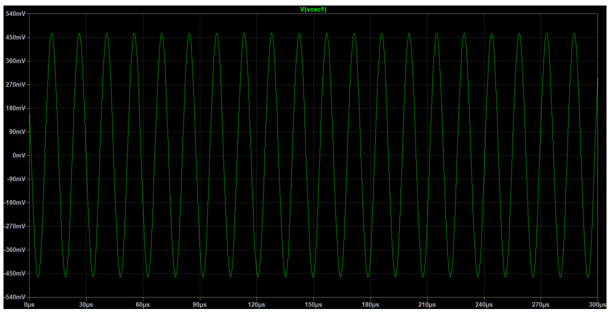
E. LT SPICE Simulations



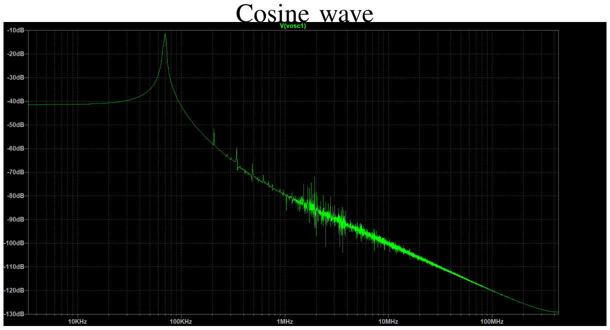
LT SPICE Circuit Simulation



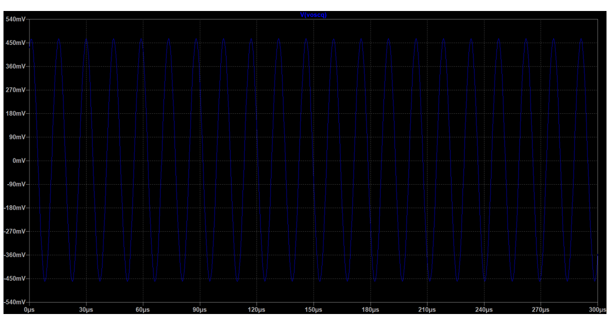
Outputs of the circuit, Phase difference = 90^o



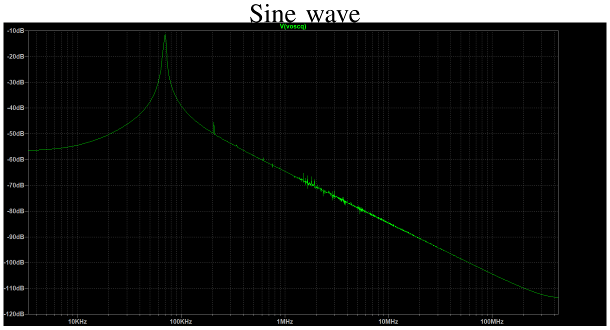
Cosine wave



fft of cosine wave

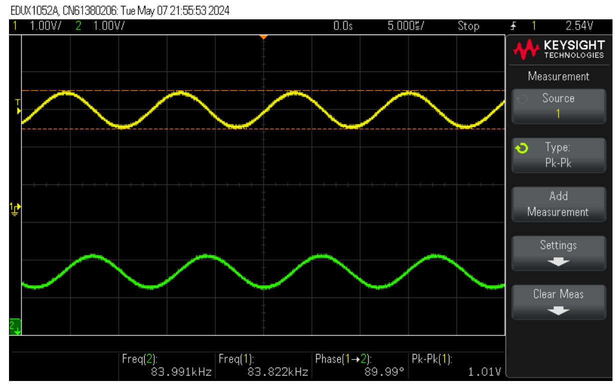


Sine wave

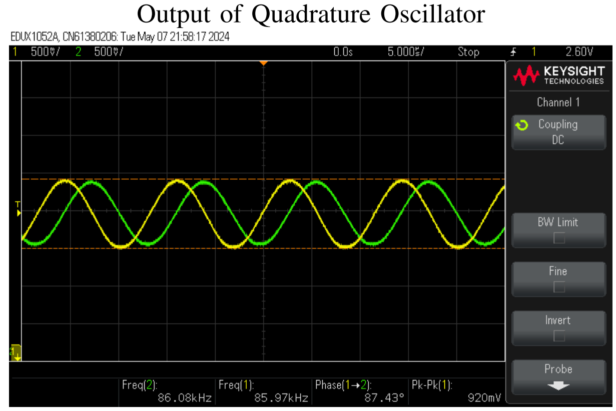


fft of sine wave

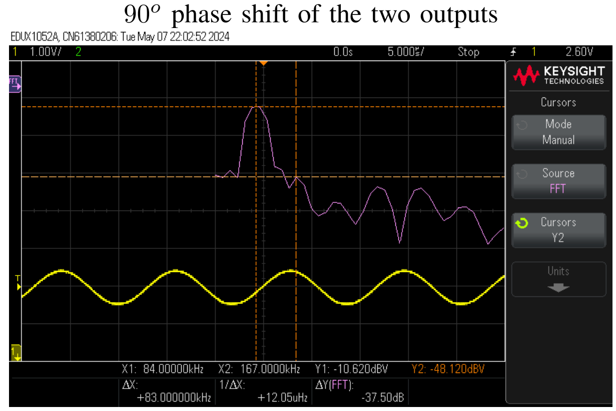
F. Circuit Implementation



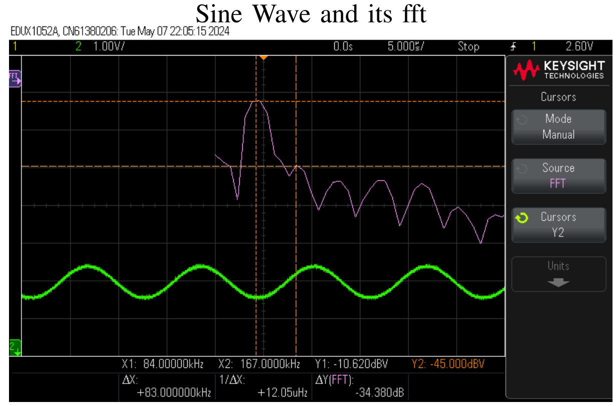
Output of Quadrature Oscillator



90^o phase shift of the two outputs



Sine Wave and its fft



Cosine Wave and its 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 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.

B. Achieving very low Internal Resistance

A MOSFET acts as a linear resistor when it is in Linear or Triode region. We can utilize it to make a Switch. Drain Current through the MOSFET in Linear Region can be represented as in Equation (11). Plot of the parabola for different values of V_{GS} is given in the following image.

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \tag{11}$$

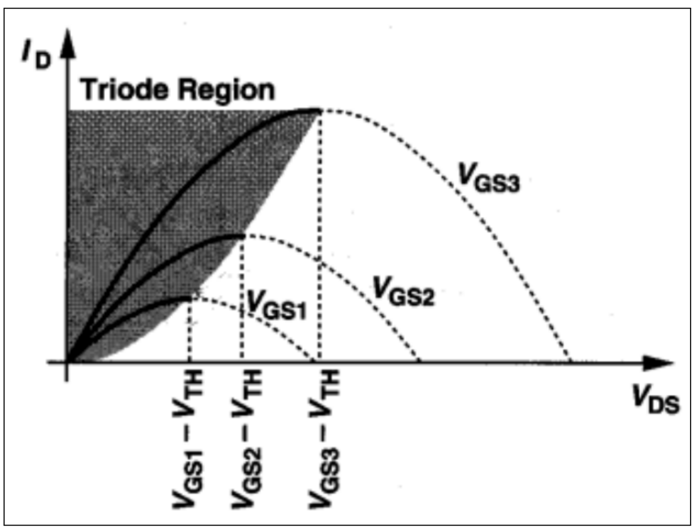


Fig. 7. I_D vs V_{DS} plots for different V_{GS}

If in Equation (11) we have $V_{DS} << 2(V_{GS} - V_{TH})$, we would get Equation (12). This region is called as Deep Triode Region.

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} \right] \tag{12}$$

This means that the Drain Current is a linear function of V_{DS}. For small V_{DS}, each parabola can be approximated by a straight line as shown in the figure below.

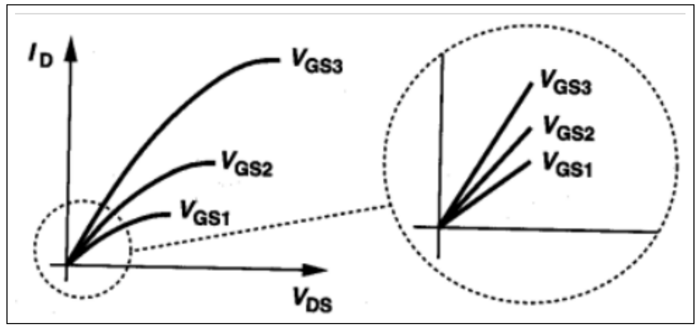


Fig. 8. Linear Operations in Deep Triode Region

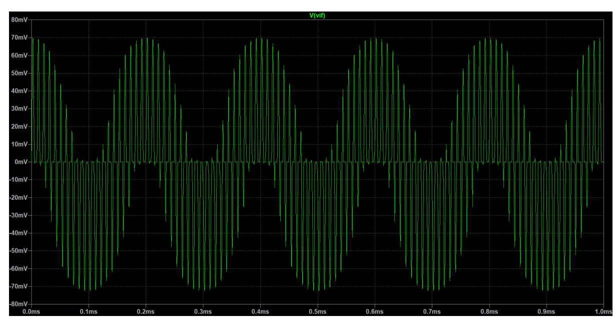
The linear relationship implies that the path from the source to drain can be represented by a linear resistor with resistance as given

$$R_{ON} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})} \tag{13}$$

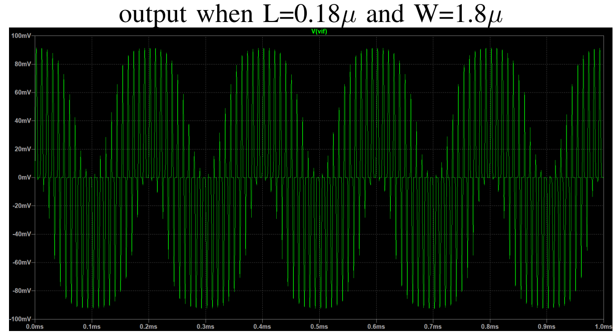
A MOSFET can therefore operate as a resistor value is controlled by the overdrive voltage $(V_{GS} - V_{TH})$ when it is in Deep Triode Region. To make the Switch Ideal, we must make this resistance very low.

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 $\frac{W}{L}$.

We can observe, in the following images, that the loss is reduced very much when we decreased the value of Length of the MOSFET.



output when L=0.18μ and W=1.8μ



output when L=0.18μ and W=9μ

C. Achieving 50% Duty Cycle

This would require you to Bias your 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., V_{osc} should operate across V_{TH}.

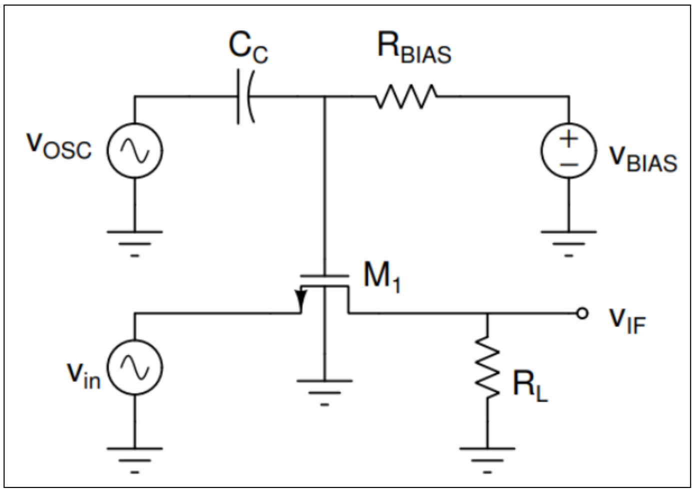


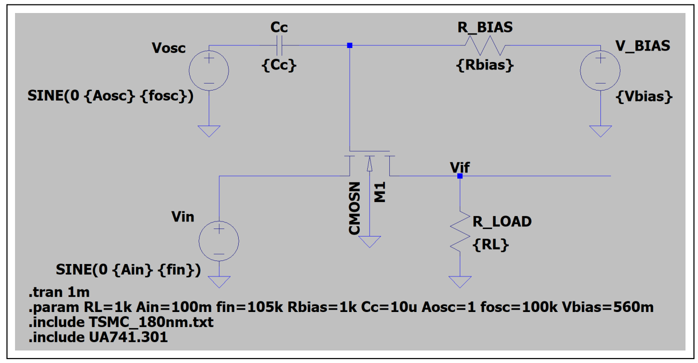
Fig. 9. Circuit of Mixer/Switch

BIASING THE GATE TERMINAL:

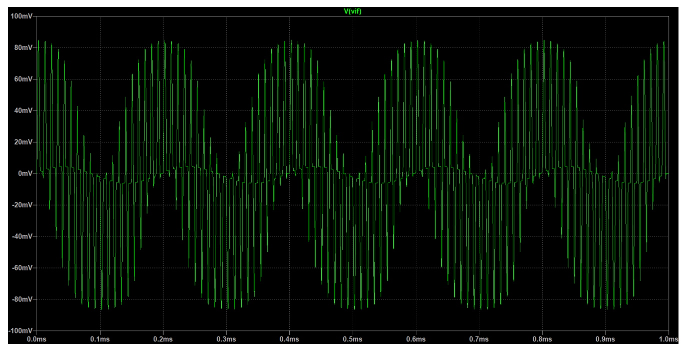
- PROBLEM
  To provide the Bias Voltage at the Gate terminal we cannot directly connect the AC and DC sources. Because when AC Signal is flowing, it will seek a very low impedance connected to Ground (as the internal resistance of an Ideal Source is very small) compared to the high Impedance at the Gate terminal. So, whole AC Current will flow through the DC Source, as it will follow the low impedance path.
  Similar discussion follows for the DC Source as well. So, unlike giving Input from the Wave Generator where we can simply specify the Offset, we need to adopt some other way to Bias the Gate terminal in real circuits.

- SOLUTION
  We use a resistor, R_{BIAS} and a capacitor, C_{BIAS} for this. To prevent the flow of DC current to the AC source we can add a Capacitor, C_{BIAS}, next to the AC source. This will isolate the AC and DC sources. Thus, preventing the flow of DC current flowing through the AC source. Any small value capacitance can be chosen. We chose $C_{BIAS} = 10\mu$. To prevent the flow of AC Current to the DC Source we can add a Resistor, R_{BIAS}, of very high resistance next to the DC source to increase the impedance. Thus, preventing the AC current to flow through the DC source. Any high value for the resistance can be chosen. We chose $R_{BIAS} = 1k$.

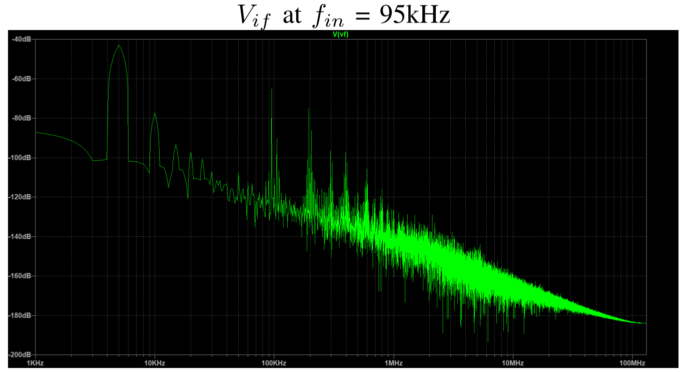
D. LT SPICE Simulations



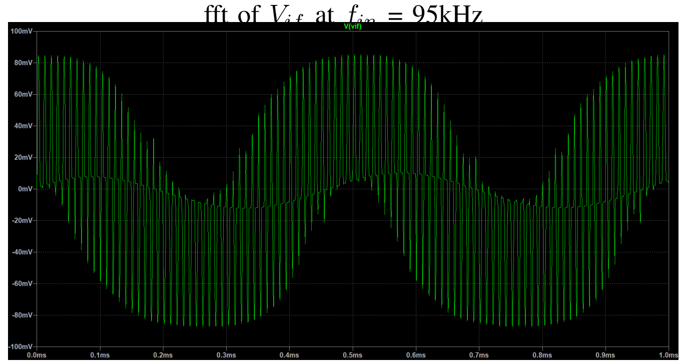
LT SPICE Circuit



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

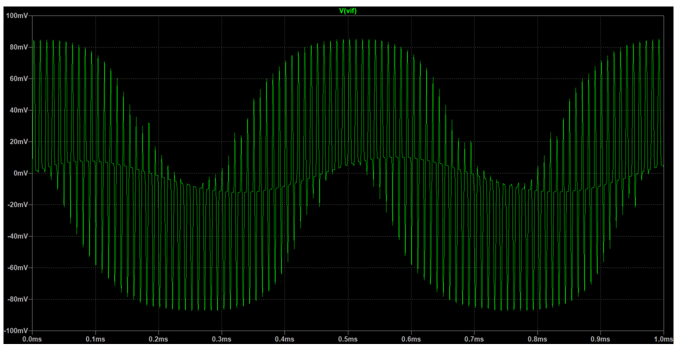


fft of V_{if} at f_{in} = 95kHz



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

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



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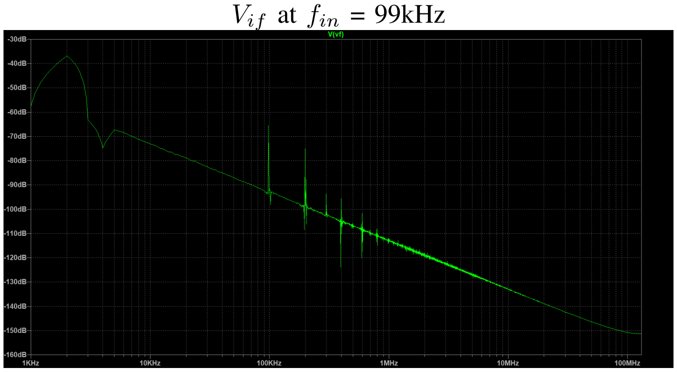

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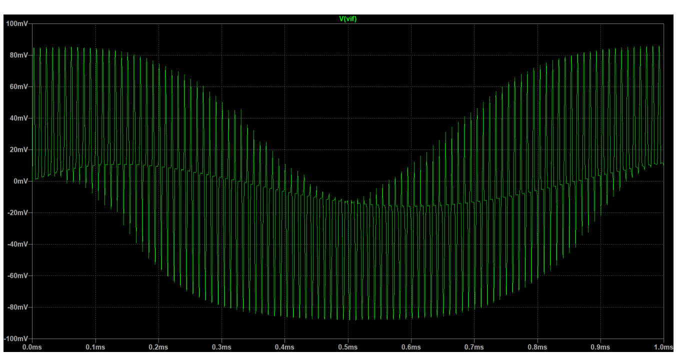

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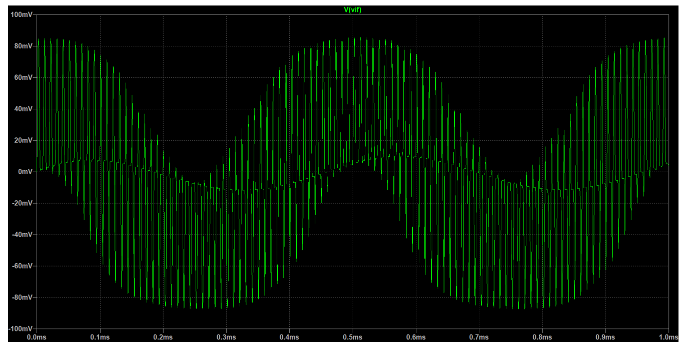
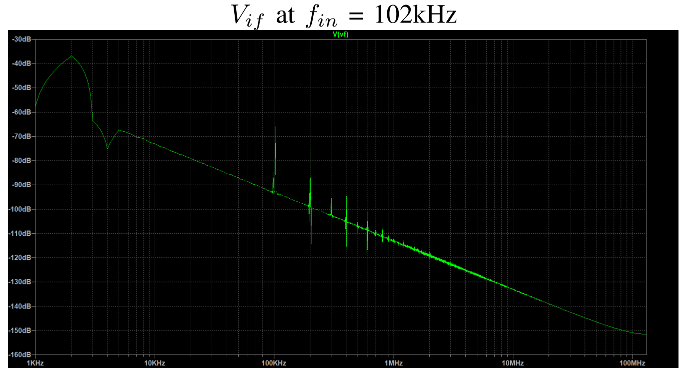
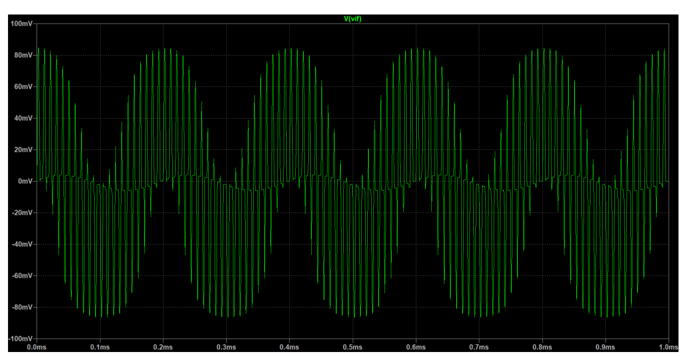


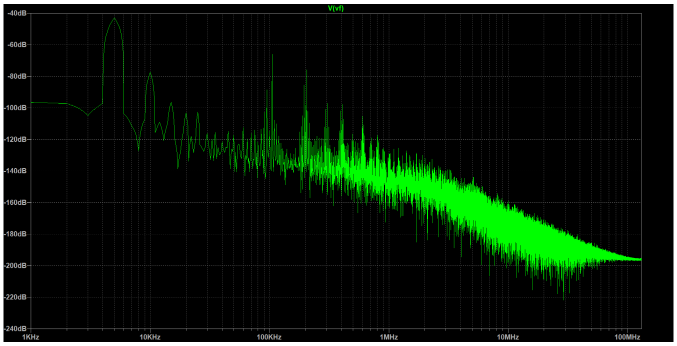
V_{if} at f_{in} = 102kHz



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

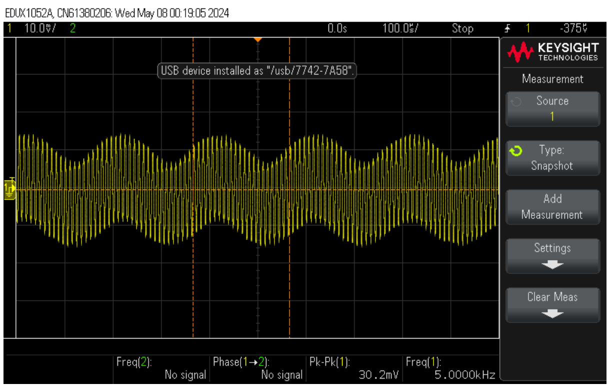


V_{if} at f_{in} = 105kHz

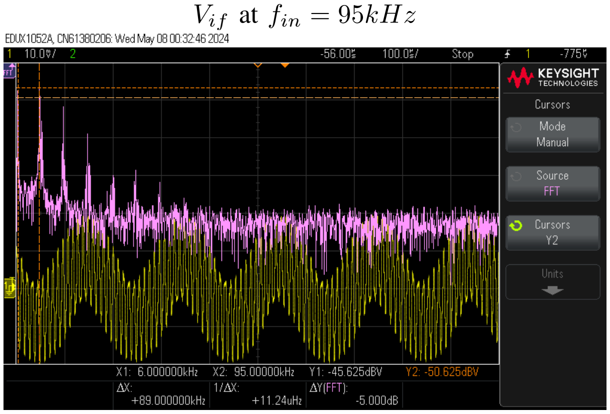


fft of V_{if} at f_{in} = 105kHz

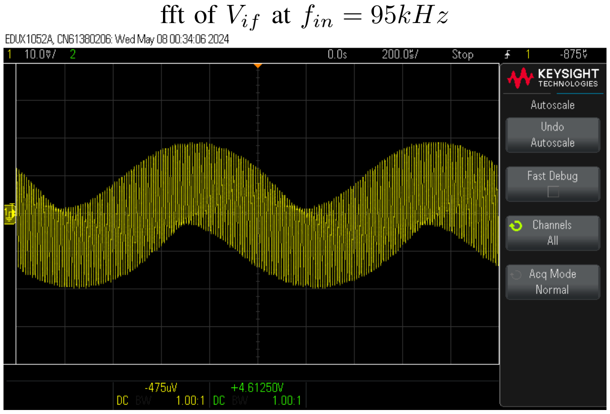
E. CIRCUIT IMPLEMENTATION



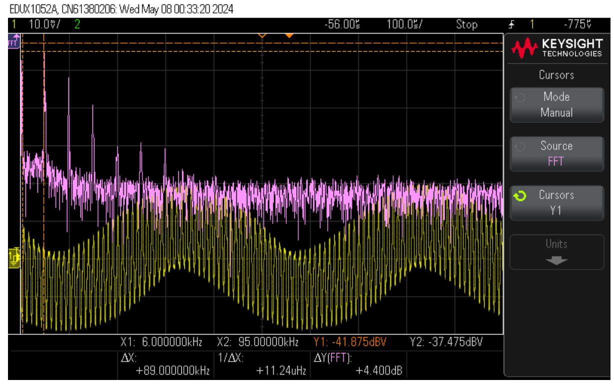
V_{if} at $f_{in} = 95kHz$



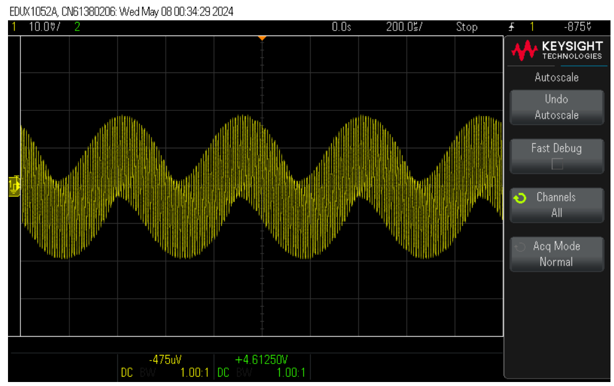
fft of V_{if} at $f_{in} = 95kHz$



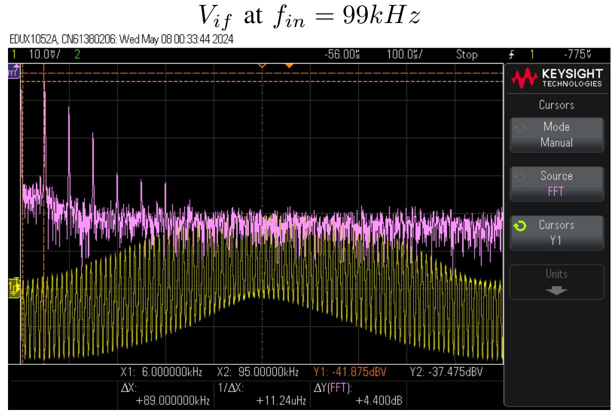
V_{if} at $f_{in} = 98kHz$



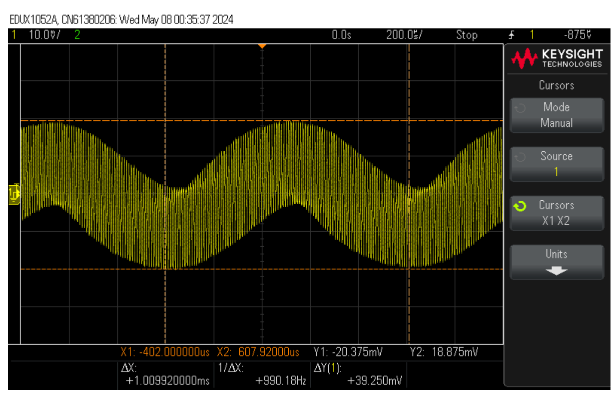
of fft of V_{if} at $f_{in} = 98kHz$



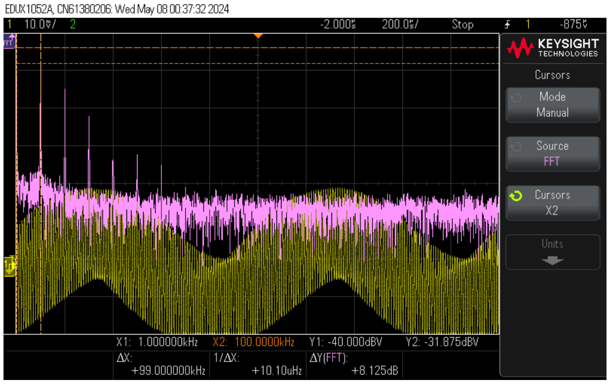
V_{if} at $f_{in} = 99kHz$



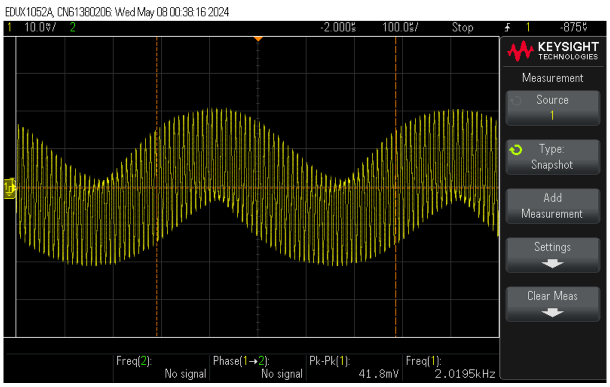
fft of V_{if} at $f_{in} = 99kHz$



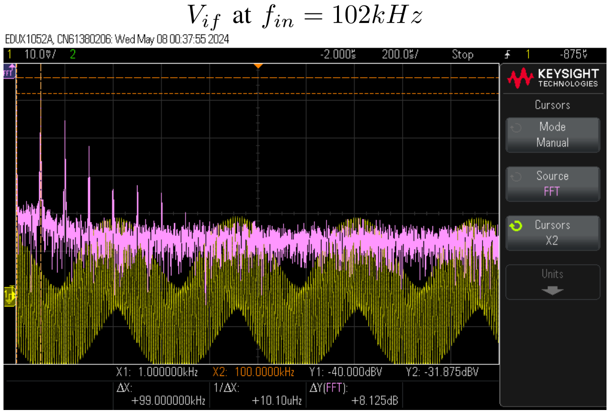
V_{if} at $f_{in} = 101kHz$



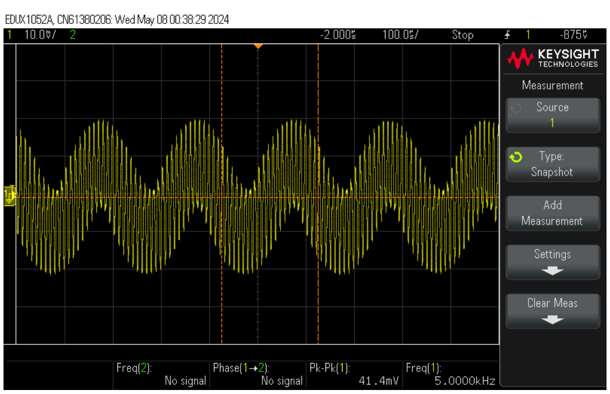
fft of V_{if} at $f_{in} = 101kHz$



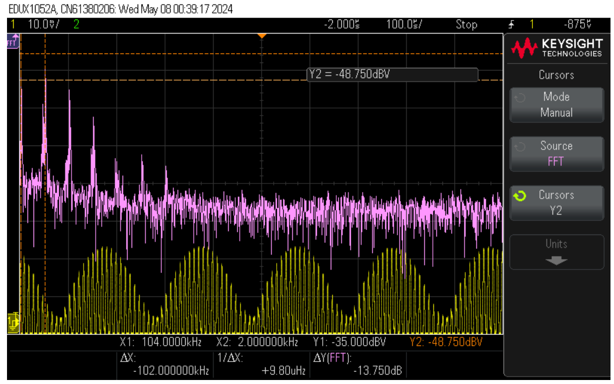
V_{if} at $f_{in} = 102kHz$



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



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



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

IV. LOW PASS FILTER

A Low Pass Filter is a circuit that can be designed to modify, reshape, or reject all unwanted high frequencies of an electrical signal and accept or pass only those signals wanted by the circuit's designer. In other words, Low pass filter is a type of filter that allows low-frequency signals and blocks high-frequency signals. The frequencies lower than a selected frequency known as the cut-off frequency are passed while any frequency higher than cut-off frequency is blocked by the filter.

In low frequency applications (up to 100kHz), passive filters are generally constructed using simple RC (Resistor-Capacitor) networks, while higher frequency filters (above 100kHz) are usually made from RLC (Resistor-Inductor-Capacitor) components. Passive filters are made up of passive components such as resistors, capacitors and inductors and have no amplifying elements (transistors, op-amps, etc.) so have no signal gain, therefore their output level is always less than the input.

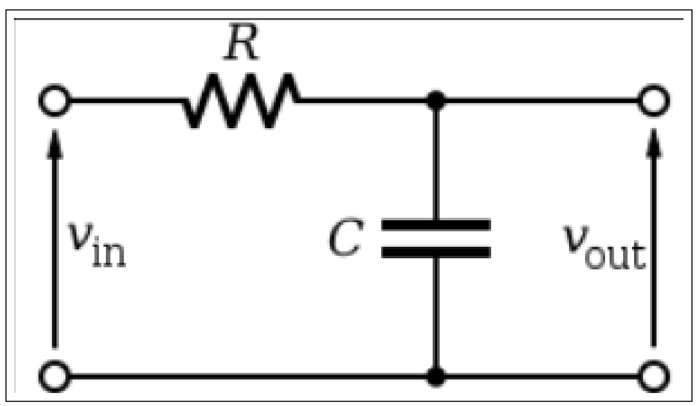


Fig. 10. An RC Low Pass Filter

A. 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.

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

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

$$V_C = V_{IN}\frac{1}{1+2\pi fRC} \tag{14}$$

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

$$V_C = V_{IN}\frac{2\pi fRC}{1+2\pi fRC} \tag{15}$$

At low frequencies the capacitive reactance, (X_C) of the capacitor is very large as compared to the resistive value of the resistor (R). So, the capacitor acts as an open circuit and the signal will appear across its terminal, which will eventually flow out as output. This can be observed from equation (14).
However, at high frequencies, the capacitive reactance (X_C) is very less than the resistance (R) of the resistor. So, when the high-frequency signal reaches the capacitor acts as a short circuit and the output becomes zero. This can be seen from equation (15).

1) Frequency Response:

$$V_{OUT} = V_{IN}\frac{X_C}{R+X_C}$$

$$V_{OUT} = V_{IN}\frac{1}{1+j2\pi fRC}$$

$$\left|\frac{V_{OUT}}{V_{IN}}\right| = \frac{1}{\sqrt{1+(2\pi fRC)^2}} \tag{16}$$

2) Cut-off Frequency: Cut-off frequency, also known as corner frequency, denoted by f_C is the selected frequency point where the output signal's power becomes $-3db$ or 70.7% of the input signal. At this frequency, the capacitive reactance X_c and resistor's resistance R become equal. The low pass filter allows frequency below the cut-off frequency and blocks any frequency higher than the cut-off frequency. Where the cut-off frequency is calculated by:

$$20log\left|\frac{V_{OUT}}{V_{IN}}\right| = -3dB$$

$$20log\left(\frac{1}{\sqrt{1+(2\pi fRC)^2}}\right) = -3dB \tag{17}$$

$$f_c = \frac{1}{2\pi RC} \tag{18}$$

To design a low pass filter with -3dB cut off frequency of

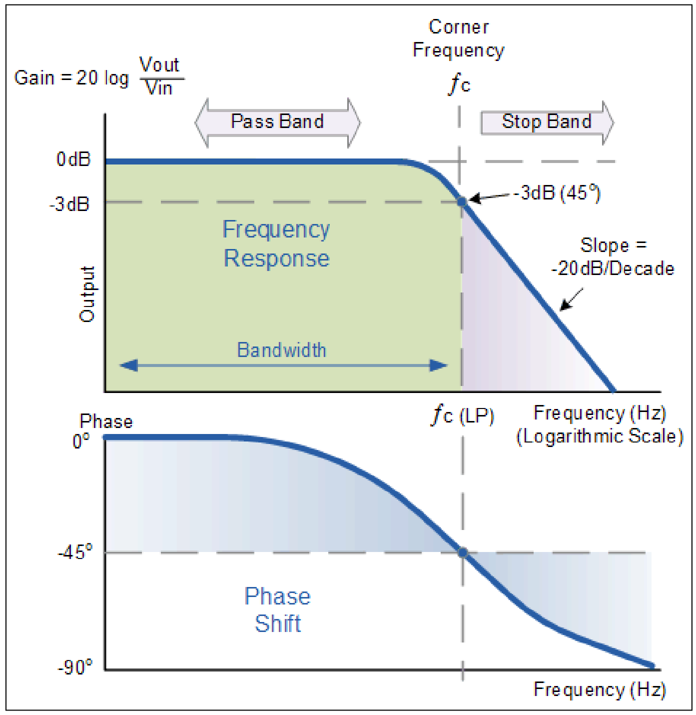


Fig. 11. LPF Frequency Response

2kHz, f_c is taken as 2kHz.

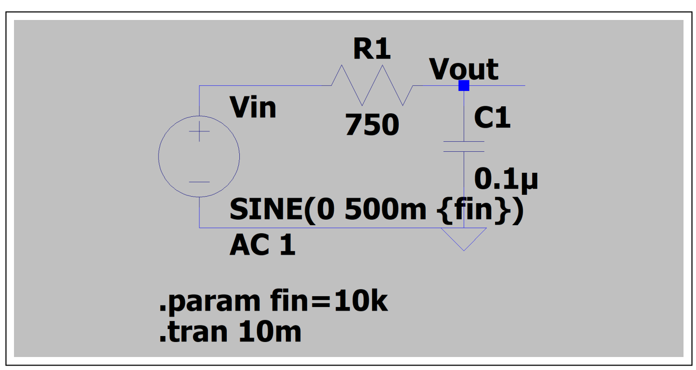
$$2\times 10^3 = \frac{1}{2\pi RC} \tag{19}$$

$$RC = 75\times 10^{-6} \tag{20}$$

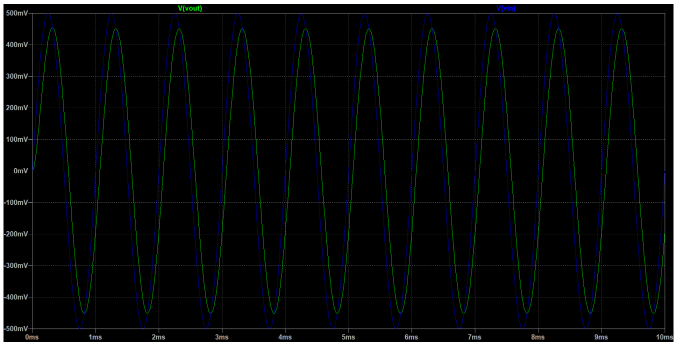
Hence, we use the following values of RC -

- $R = 750\Omega$
- $C = 0.1\mu F$
- $RC = 75\mu s$
- $f_c = 2122Hz$

B. LT SPICE Simulations

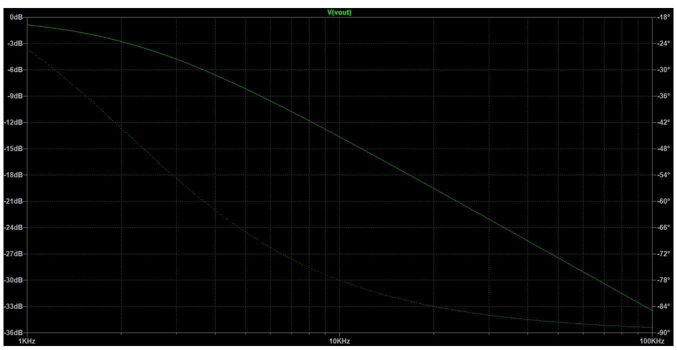


LT SPICE Circuit implementation



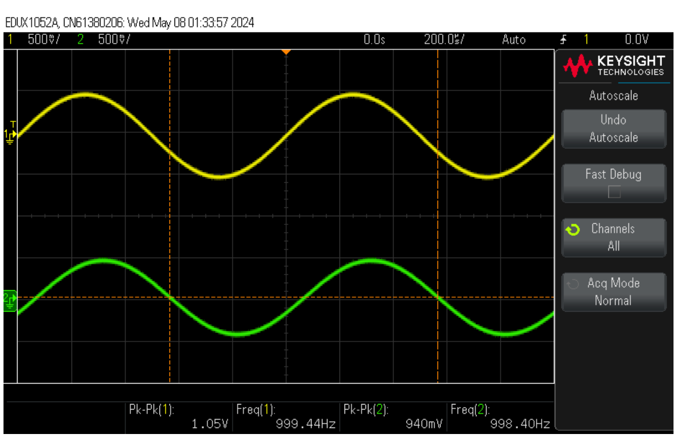
Low Pass Filter at 1kHz

Low Pass Filter at 10kHz

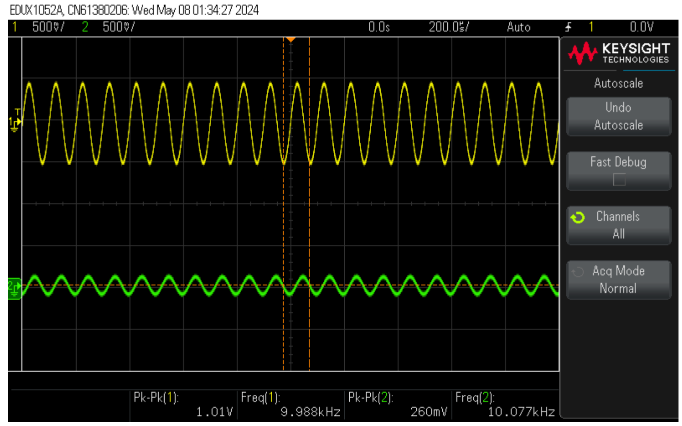


Frequency Response

C. Circuit Implementation



Low Pass Filter at 1kHz



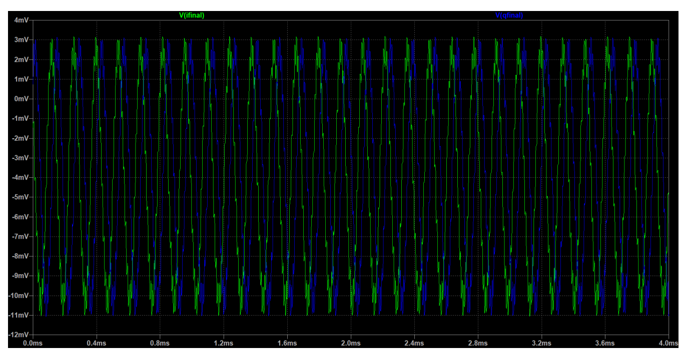
Low Pass Filter at 10kHz

V. COMPLETE SECTION

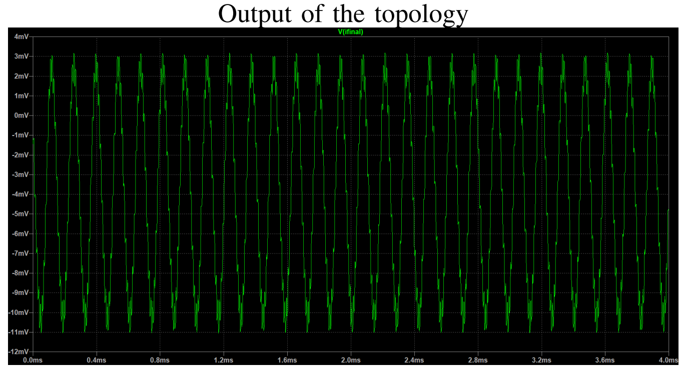
Connecting all the building blocks – Oscillator, Mixer and Filter, the final circuit is implemented.

The final circuit will produce two waves IF_I and IF_Q which are the in-phase and the quadrature-phase components of the IF signal. These signals have a phase difference of 90°.

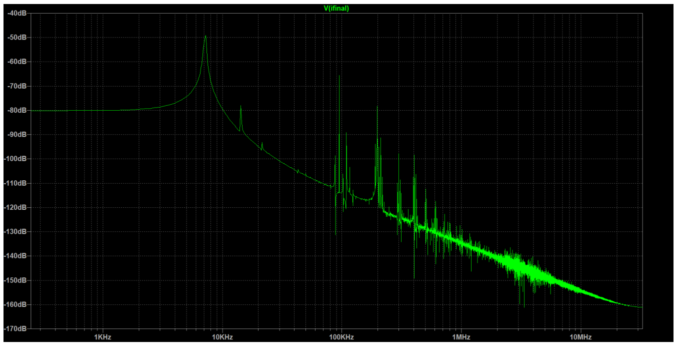
A. LT SPICE Simulations



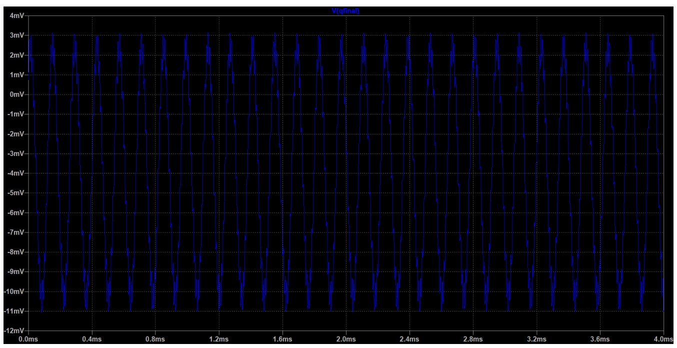
Output of the topology



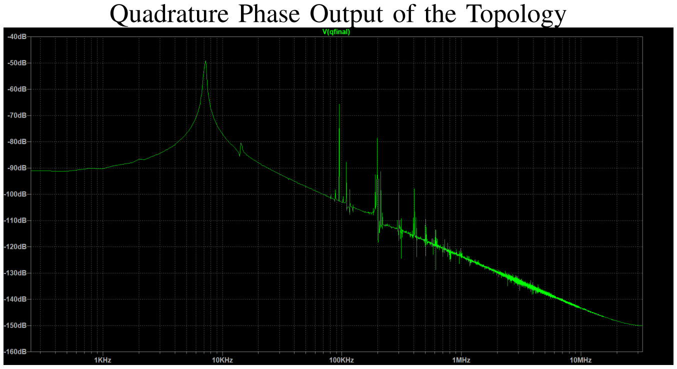
In-Phase Output of the Topology



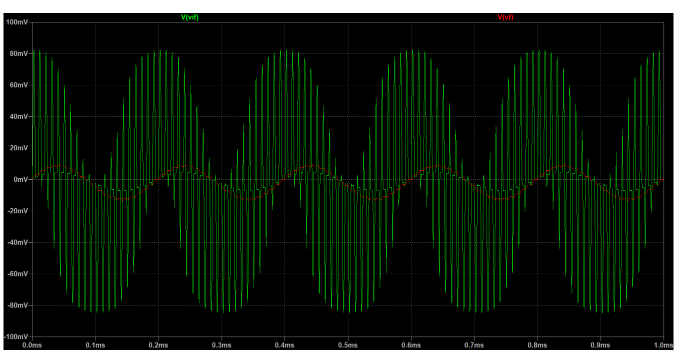
fft of In Phase Output



Quadrature Phase Output of the Topology



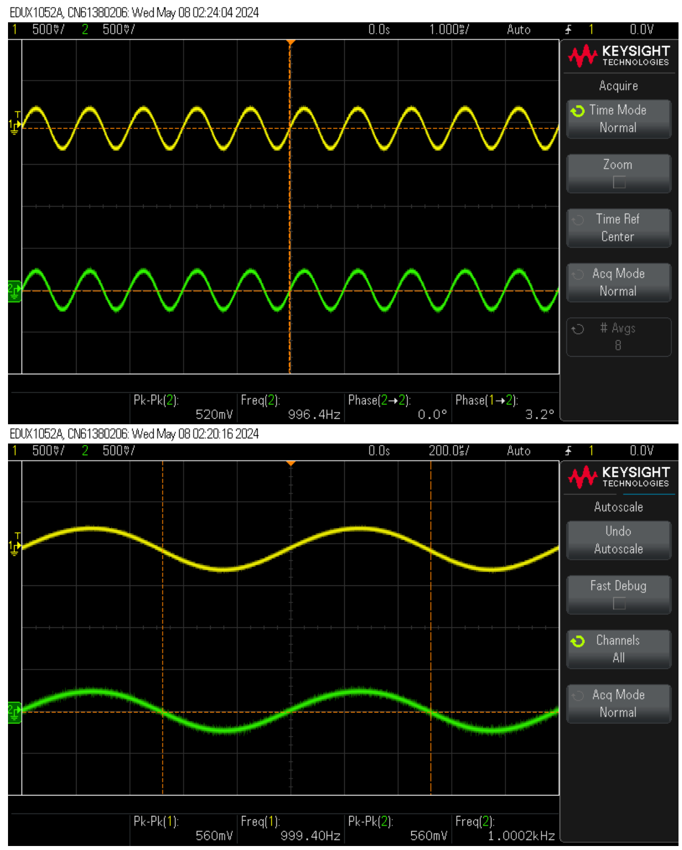
fft of Quadrature Phase Output



Input and Output of the mixer

fft of the output of the mixer after passing through LPF

B. Circuit Implementation



Output of the Circuit

C. Final Results

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

D. Performance Summary and Comparison

Hence we find that our implementation works well within a few experimental errors.

Parameters	Simulated	Measured	Expected
Oscillator Frequency	100 kHz	98.7 kHz	100 kHz
Oscillator Amplitude (I-phase)	950mV	800mV	1V
Oscillator Amplitude (Q-phase)	950mV	800mV	1V
Input Frequency	100kHz	100kHz	100kHz
IF	2kHz	2KHz	2kHz
Supply	2.5V	3V	2.5V
V_{BIAS}	560mV	1.8V	1.7V
C_c	10μF	10μF	10μF
R_{BIAS}	10kΩ	10kΩ	10MΩ
R_1, R_2, R_3	1.5$k\Omega$	1.5$k\Omega$	1.5$k\Omega$
C_1, C_2, C_3	1nF	1nF	1nF

TABLE I
PERFORMANCE SUMMARY AND COMPARISON

ACKNOWLEDGEMENT

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REFERENCES

[1] Behzad Razavi, Design of Analog CMOS integrated Circuits.
[2] Rahsoft.com, understanding quadrature down conversion.
[3] Babak Bastani, Edwin E Bautisa, Geetha Nagaraj and Joe Heck, "A Quadrature Down Converter For Direct Conversion Receivers with High 2nd and 3rd Order Intercept"
[4] Ron Mancini, "Design of op amp Sine Wave Oscillator".
[5] Ralph Holzel, "A Simple Wde-Band Sine Wave Quadrature Oscillator".
[6] Adel S. Sedra, Kenneth C. Smith, Microelectronic Circuits.
[7] Texas Instruments Incorporated, Design of op amp sine wave oscillators
[8] Asad A. Abidi, Direct-Conversion Radio Transceivers for Digital Communications