COLPITTS OSCILLATOR

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***Abstract*—This project embarks on the intricate construction of a COLPITTS OSCILLATOR, a fundamental electronic circuit widely used in various communication and signal processing applications.**

In the second phase of the project, the constructed Colpitts oscillator is ingeniously applied in the realms of MODULATION and DEMODULATION . Leveraging the oscillator's stable and tunable output, it serves as the carrier signal for modulation purposes.

I. PART 1 : COLPITTS OSCILLATOR

A. Objective

The primary objective of this project is to design, simulate, and construct a **COLPITTS OSCILLATOR** circuit capable of generating stable and tunable sinusoidal oscillations within a specified frequency range. The goal is to achieve a reliable Colpitts oscillator configuration that can serve as a fundamental building block for various electronic applications, particularly in communication systems and signal processing.

B. Need for Colpitts Oscillator

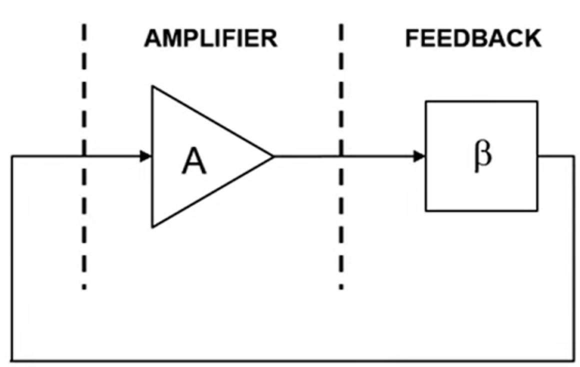

Fig. 1. Basic Oscillator Design

The basic design of an oscillator with an amplifier and feedback typically involves the following components and principles:

Amplifier Stage: The oscillator usually starts with an amplification stage, which can be a transistor, operational amplifier (op-amp), or other amplification devices. This stage provides gain to the input signal.

Feedback Network: A portion of the output signal from the amplifier is fed back to its input with the help of a feedback network. This network can consist of passive components like resistors, capacitors, and inductors. The feedback network is crucial for sustaining oscillations by providing positive feedback.

In oscillators that use op amps, we can pretty much treat the op amp as an ideal amplifier. Op amps have **very high input impedance and very low output impedance**, so they very closely resemble ideal amplifiers, but op-amps have limitations. Op amps, for example, the LM 741 op amp starts to **roll off at higher frequencies**. In other words, the gain starts to resemble less and less the nominal value than what we calculate .Op-amps generally don't work very well at high frequencies.

If we attempt to design an RC oscillator at radio frequencies, where higher frequencies are involved, we would require very small values of resistors and capacitors. This necessity for extremely small component values can make the oscillator unreliable due to factors such as parasitic effects and manufacturing tolerances.

Instead, it's more practical to use an LC oscillator for radio frequencies. LC oscillators utilize inductors and capacitors in the feedback network, offering a more stable and reliable solution. Among the various LC oscillator configurations, the **Colpitts oscillator** serves as a popular choice.

C. Non Ideal Oscillator Design

In the Colpitts oscillator, a combination of capacitors and inductors forms a resonant circuit that sets the oscillation frequency. This configuration allows for easier tuning and adjustment of the oscillator frequency, making it suitable for applications in radio frequency (RF) circuits and communication systems.

In this model , we replace the amplifier model with that of a non-ideal amplifier. This non - ideal amplifier that has a **non-infinite input impedance and a non-zero output impedance**.

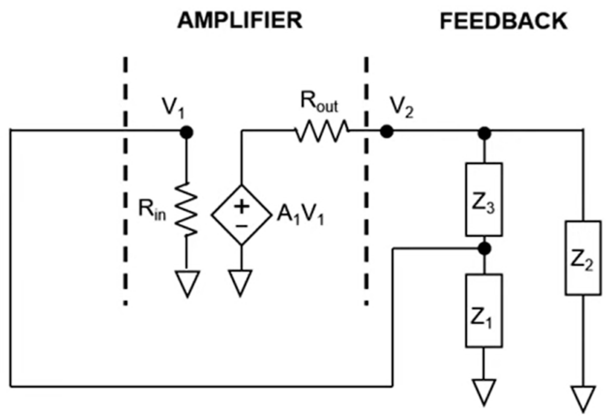

Fig. 2. Non - ideal Amplifier Design

This particular model is appropriate when we use a transistor amplifier. The gain A of the entire amplifier is certainly going to be less than the gain A_1 of the controlled source.

The feedback network of the oscillator consists of three elements, labeled as Z_1, Z_2, and Z_3, which refer to the impedance of the particular circuit element. Depending on the oscillator's design, these elements may be either inductors or capacitors.

D. LC Oscillation Base Design

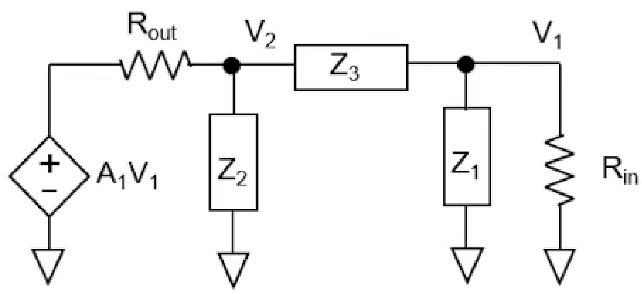

Fig. 3. Simplified Design of Non - ideal Amplifier

To begin our analysis of the circuit and determine the frequency of oscillation, let's unwrap the components. Firstly, we'll apply voltage division to ascertain the voltage V_1 across V_2. Z_1 and R_{in} are in parallel, with Z_3 serving as our series element.

$$\frac{V_1}{V_2} = \left(\frac{R_{\text{in}} \parallel Z_1}{R_{\text{in}} \parallel Z_1 + Z_3}\right) \tag{1}$$

We can once again apply voltage division to determine the ratio of voltage V_2 to voltage $A_1 \cdot V_1$. This is given by:

$$\frac{V_2}{A_1 V_1} = \frac{Z_2 \parallel (R_{\text{in}} \parallel Z_1 + Z_3)}{(Z_2 \parallel (R_{\text{in}} \parallel Z_1 + Z_3)) + R_{\text{out}}}$$

$$\frac{V_2}{A_1 V_1} = \frac{(Z_2(R_{\text{in}} \parallel Z_1 + Z_3))}{((R_{\text{in}} \parallel Z_1 + Z_3) + Z_2)} \Bigg/ \left(\frac{(Z_2(R_{\text{in}} \parallel Z_1 + Z_3))}{((R_{\text{in}} \parallel Z_1 + Z_3) + Z_2)} + R_{\text{out}}\right)$$

$$\frac{V_2}{V_1} = A_1 \cdot \frac{Z_2(R_{\text{in}} \parallel Z_1 + Z_3)}{Z_2(R_{\text{in}} \parallel Z_1 + Z_3) + R_{\text{out}}(R_{\text{in}} \parallel Z_1 + Z_3 + Z_2)} \tag{2}$$

We make the assumption that the input impedance is high, even when utilizing a transistor. This assumption is reasonable since the input impedance looking into the base of a bipolar junction transistor, for instance, tends to be very high. Therefore, we neglect the input impedance in expressions (1) and (2) .

Neglecting the input impedance in expression (1) results in

$$\frac{V_1}{V_2} = \frac{Z_1}{Z_2 + Z_3} \tag{3}$$

Neglecting the input impedance in expression (2) results in

$$\frac{V_2}{V_1} = A \cdot \frac{Z_2(Z_1 + Z_3)}{(Z_2(Z_1 + Z_3)) + R_{\text{out}}(Z_1 + Z_2 + Z_3)} \tag{4}$$

Mutliplying expressions (3) and (4) , we get :

$$\left(\frac{V_1}{V_2} \cdot \frac{V_2}{V_1}\right) = \frac{Z_1}{Z_1 + Z_3} \cdot \left(A_1 \cdot \frac{Z_2(Z_1 + Z_3)}{Z_2(Z_1 + Z_3) + R_{\text{out}}(Z_1 + Z_3)}\right)$$

Substitute $Z = jX$, where X is the reactance ($X = \omega L$ for inductors and $X = -\frac{1}{\omega C}$ for capacitors)

$$1 = \frac{X_1 \cdot X_2 \cdot A_1}{X_2(X_1 + X_3) - jR_{\text{out}}(X_1 + X_2 + X_3)}$$

$$X_2(X_1 + X_3) - jR_{\text{out}}(X_1 + X_2 + X_3) = X_1 \cdot X_2 \cdot A_1 \tag{5}$$

From the above expression (5) , we observe that there is no imaginary term in the RHS . So the coefficient of j in LHS should be equal to 0 and then we equate the real parts on both sides .

Equating the coefficient to 0 , we obtain :

$$\mathbf{X_1 + X_2 + X_3 = 0} \tag{5}$$

Therefore, the sum of the three reactive elements in this circuit must be zero.

Equating the real parts , we obtain :

$$\mathbf{A_1} = -\frac{\mathbf{X_2}}{\mathbf{X_1}} \quad (6)$$

Gain of the amplifier has to be minus X2 over X1 for this oscillator to have non-zero voltages V1 and V2. The negative sign indicates that the amplifier is **inverting** .

E. Design of Colpitts Oscillator

To design a practical circuit, we need to substitute in inductors or capacitors for these reactive elements. In the Colpitts oscillator, reactive elements 1 and 2 are capacitors, and reactive element 3 is an inductor. For an inverting amplifier, we can use a standard **Common Emitter Transistor configuration**.

$$X_1 = -\frac{1}{\omega C_1} \quad ; \quad X_2 = -\frac{1}{\omega C_2} \quad ; \quad X_3 = \omega L_3$$

From equation (6) , gain is given by :

$$A_1 = -\frac{\frac{1}{\omega C_2}}{\frac{1}{\omega C_1}} = -\frac{C_1}{C_2}$$

When we design this circuit, we need to ensure that the magnitude of the gain exceeds C_1 over C_2 so that the oscillation can get started from noise and so that we can overcome any losses in the circuit.

From equation (5) , we can obtain the frequency of oscillations :

$$X_1 + X_2 + X_3 = 0$$
$$-\frac{1}{\omega C_1} - \frac{1}{\omega C_2} + \omega L_3 = 0$$
$$-C_2 - C_1 + \omega^2 L_3 C_1 C_2 = 0$$
$$\boldsymbol{\omega} = \sqrt{\frac{\boldsymbol{C_1 + C_2}}{\boldsymbol{C_1 C_2 L_3}}}$$

If we want to make the Colpitts oscillator tunable in frequency, it wouldn't be a great idea to adjust capacitors C_1 or C_2, because that would change the conditions on the gain. But by adjusting inductor L_3, then we can change the frequency of oscillation without affecting the gain.

So, the two most important oscillation conditions for designing an oscillator are as follows:

1. Frequency of Oscillation:

$$\boldsymbol{\omega} = \sqrt{\frac{\boldsymbol{C_1 + C_2}}{\boldsymbol{C_1 C_2 L_3}}}$$

2. Gain of the Oscillator:

$$\boldsymbol{A_1} = -\frac{\boldsymbol{C_1}}{\boldsymbol{C_2}}$$

F. Working of Colpitts Oscillator

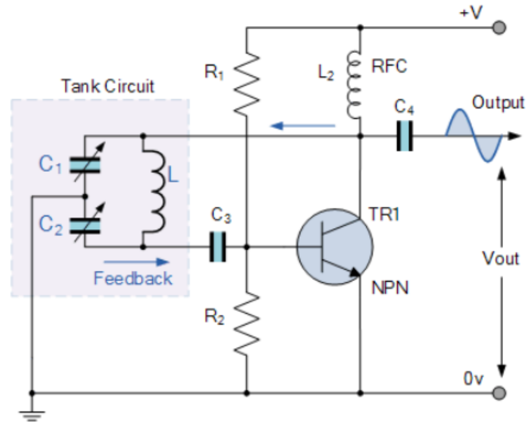

Fig. 4. Basic Colpitts Oscillator Circuit

The emitter terminal of the transistor is effectively connected to the junction of the two capacitors, C_1 and C_2, which are connected in series and act as a simple voltage divider. When the power supply is firstly applied, capacitors C_1 and C_2 charge up and then discharge through the coil L. The oscillations across the capacitors are applied to the base-emitter junction and appear in the amplified at the collector output.

Resistors, R_1 and R_2 provide the usual stabilizing DC bias for the transistor in the normal manner while the additional capacitors act as a DC-blocking bypass capacitors. A radio-frequency choke (RFC) is used in the collector circuit to provide a high reactance (ideally open circuit) at the frequency of oscillation, (fr) and a low resistance at DC to help start the oscillations.

The amount of feedback is determined by the ratio of C_1 and C_2. These two capacitances are generally "ganged" together to provide a constant amount of feedback so that as one is adjusted the other automatically follows.

The configuration of the transistor amplifier is of a Common Emitter Amplifier with the output signal 180° out of phase with regards to the input signal. The additional 180° phase shift required for oscillation is achieved by the fact that the two capacitors are connected together in series but in parallel with the inductive coil, resulting in an overall phase shift of the circuit being zero or 360°.

The amount of feedback depends on the values of C_1 and C_2. We can see that the voltage across C_1 is the the same as the oscillators output voltage, Vout and that the voltage across C_2 is the oscillators feedback voltage. Then the voltage across C_1 will be much greater than that across C_2.

Therefore, by changing the values of capacitors, C_1 and C_2 we can adjust the amount of feedback voltage returned to the tank circuit. However, large amounts of feedback may cause the output sine wave to become distorted, while small amounts of feedback may not allow the circuit to oscillate.

Then the amount of feedback developed by the Colpitts oscillator is based on the capacitance ratio of C_1 and C_2 and is what governs the the excitation of the oscillator. This ratio is called the **Feedback Fraction** and is given simply as:

$$\text{Feedback Fraction} = \left(\frac{C_1}{C_2}\right) \times 100\%$$

G. *Frequency of Oscillation*

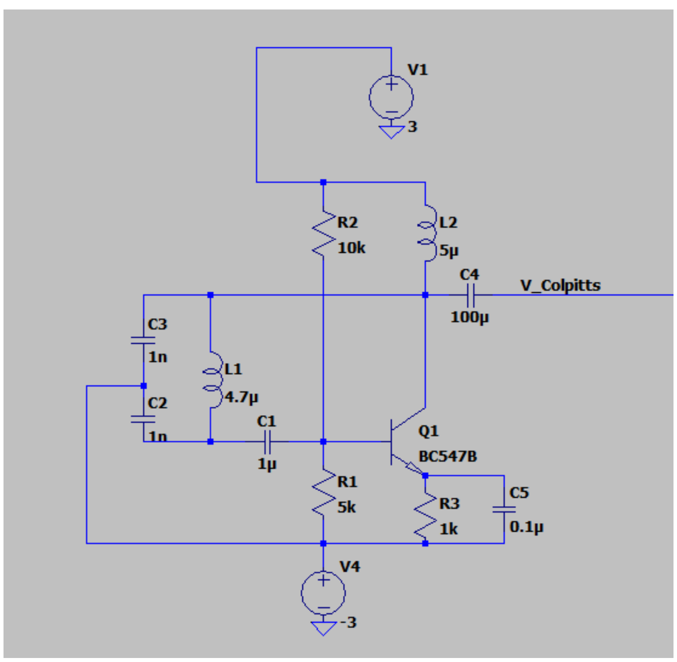

Fig. 5. Actual Colpitts Oscillator

From the above circuit, we observe that the tank circuit contains two capacitors of value $C_1 = 1\,\text{nF}$ and $C_2 = 1\,\text{nF}$, and an inductor of value $L_3 = 5\,\mu\text{H}$.

Using the frequency of oscillation formula that we obtained:

$$\begin{aligned}
\omega &= \sqrt{\frac{C_1 + C_2}{C_1 C_2 L_3}} \\
&= \sqrt{\frac{1\,\text{nF} + 1\,\text{nF}}{(1\,\text{nF}) \times (1\,\text{nF}) \times (4.7\,\mu\text{H})}} \\
&= \sqrt{\frac{2\,\text{nF}}{(1\,\text{nF})^2 \times (4.7\,\mu\text{H})}} \\
&= \sqrt{\frac{20}{4.7}} \times 10^7\ \text{rad/s} \\
&\approx \sqrt{4.2553} \times 10^7\ \text{rad/s} \\
&\approx 2.0628 \times 10^7\ \text{rad/s}
\end{aligned}$$

To obtain the frequency , we use :

$$\begin{aligned}
f &= \frac{\omega}{2\pi} \\
&= \frac{2.0628 \times 10^6}{2\pi} \\
&\approx \frac{2.0628 \times 10^6}{6.283} \\
&\approx 3.2847\,\text{MHz}
\end{aligned}$$

So, the frequency of the Colpitts Oscillator: $f = \mathbf{3.294}\,\text{MHz}$

H. *Simulation Results*

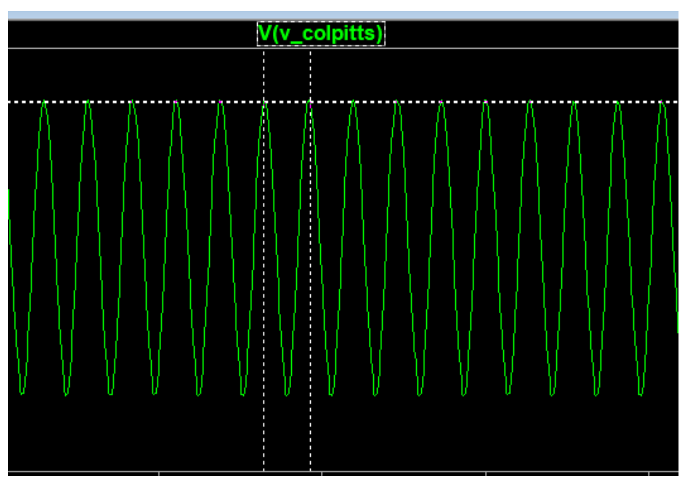

Fig. 6. Simulated Oscillator output

By using cursor , we can measure the frequency and the obtained frequency is given by :

From the below figure , we observe that the frequency of the Simulated Colpitts Oscillator: $f = \mathbf{3.7}\,\text{MHz}$

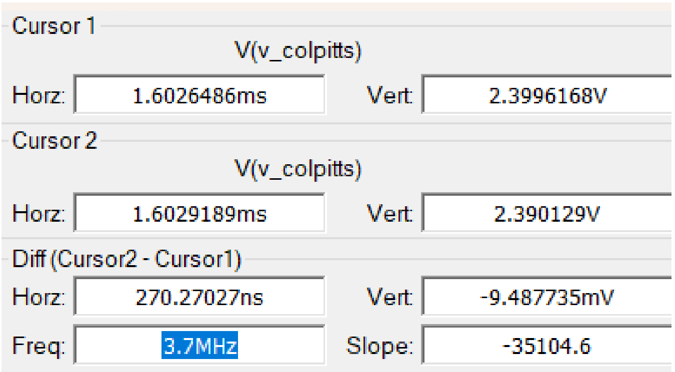

Fig. 7. Simulated Frequency of Oscillation

I. *Hardware Outputs - DSO*

From the provided DSO output in figure 8, it's evident that the frequency hovers around **3.83MHz**. This deviation from the anticipated value of **3.2847MHz** can be attributed to two primary factors:

1) **Inclusion of R_{in} Contribution:** Initially, in computing the expected oscillation frequency, the contribution of R_{in} was neglected due to its considerably high value. However, in practical scenarios, although R_{in} is high, it cannot be entirely disregarded and must be factored in for more precise results.
2) **Component Tolerances:** The nominal values of the inductors and capacitors might not perfectly align with their actual values due to manufacturing tolerances or environmental factors. This slight deviation in the physical setup from the intended values leads to variations in the oscillation frequency.

In summary, the observed frequency discrepancy can be attributed to the combined effects of neglecting R_{in} contribution and the tolerance variations in component values, highlighting the importance of accounting for these factors for accurate frequency predictions.

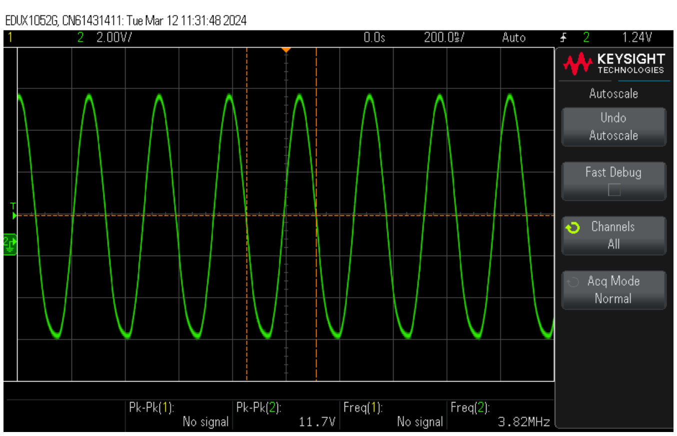

Fig. 8. Hardware DSO Frequency of Oscillation

J. *Challenges encountered*

1. Investigations revealed that the circuit's sensitivity to capacitor values resulted in fluctuations in the gain whenever capacitors were altered. Consequently, the decision was made to focus on adjusting the values of the inductors.

2. During the initial construction phase of the circuit, the absence of the Radio Frequency Choke (RFC) was overlooked. This omission delayed the initiation of oscillations, thereby adversely affecting the oscillator.

II. PART 2 :APPLICATION OF COLPITTS OSCILLATOR

A. *Amplitude Modulation*

Amplitude Modulation is a type of modulation technique in which the amplitude of a high frequency carrier signal is varied based on the shape of the message signal. A message signal is typically a low frequency (few kHz) signal. A low frequency signal has a high wavelength and therefore requires a very long antenna, which is not feasible. Moreover, a low frequency signal has much lower noise and interference immunity compared to a high frequency signal. Due to these reasons we cannot directly transmit the message signal. Therefore, there is a need to transmit it using a high frequency (few MHz) carrier signal. Let us consider $m(t)$ as the message signal and $c(t)$ as the carrier signal. Typically, $c(t) = \cos(2\pi f_c t)$ where f_c is a high frequency. The amplitude modulated signal $s(t)$ can be represented as shown below:

$$s(t) = m(t)\cos(2\pi f_c t)$$

B. *Switching Modulation*

A Switching Modulator is a circuit used carry out amplitude modulation (AM). It consists of a switch-like circuit in which the message signal is switched on and off at the rate of the carrier frequency. Figure 8 shows the circuit of the switching modulator.

It consists of a message signal (m(t)) and a carrier signal of frequency f_c. Also it consists of 2 oppositely-faced diodes and a resistor across which we can get the output. The carrier signal should have a magnitude greater than that of the message signal. As f_c is a very high frequency, the diodes will switch on and off rapidly at the rate of carrier frequency. When the series voltage of message and carrier signal is positive, one of the diode will be on and when it is negative, the other diode will be on. Therefore, the diodes act as a square wave(w(t)) which we are multiplying with the message signal. The Fourier series expansion of w(t) is as shown below:

$$w(t) = 1/2 + (\pi/2)(\ \cos(2\pi f_c t)\ -\ (1/3)cos(6\pi f_c t)\ +\ ...)$$

Therefore, on multiplying it with m(t):

$$y(t) = m(t).[\ 1/2 + (\pi/2)(\ \cos(2\pi f_c t) - (1/3)cos(6\pi f_c t) + ...)]$$

Ignoring the smaller terms, we get:

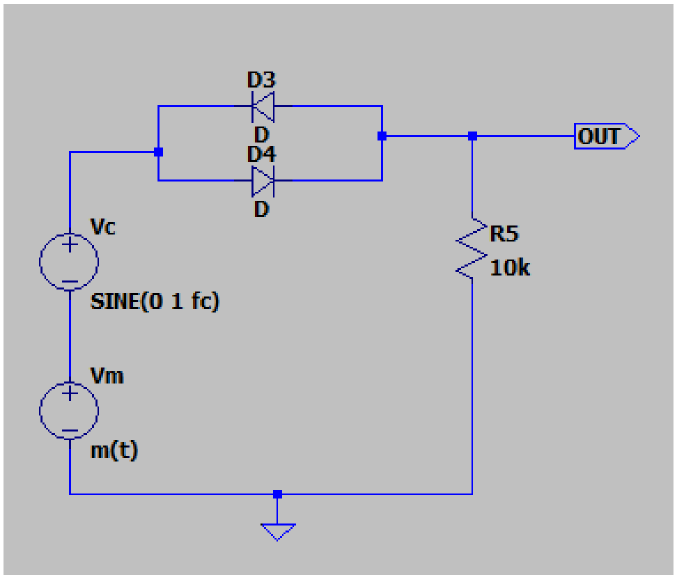

Fig. 9. Switching Modulator

$$y(t) = (\pi/2)m(t)\cos(2\pi f_c t)$$

This is the required amplitude modulated signal along with a scaling factor.

C. Demodulation of Amplitude Modulated Signal

The amplitude modulated signal obtained at the output of the switching modulator consists of the message signal frequency as well as the carrier frequency. In order to separate the message signal from the carrier signal, we can pass the amplitude modulated signal through a simple low pass filter which has a cut-off frequency between that of the message and carrier signal. Figure 10 shows the low-pass filter circuit

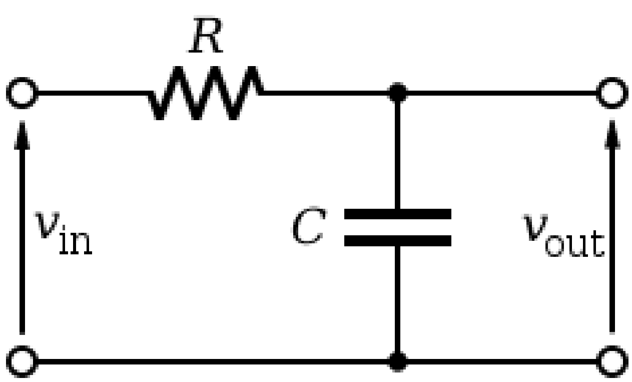

Fig. 10. Low-pass filter

D. Simulation Results

Figure 11 shows the output of the switching modulator obtained in the simulation. Here, the carrier frequency is 3.7 MHz and the message signal is a cosine wave of frequency 20 kHz and amplitude 1 V.

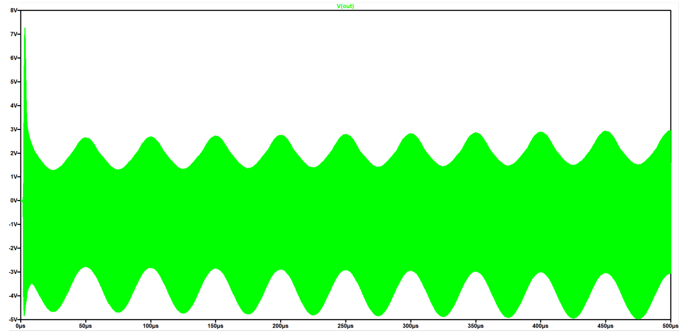

Fig. 11. Simulated Amplitude Modulator Output

Also, figure 12 shows the output obtained after demodulating the amplitude modulated signal using a low pass filter. We can notice that we get an attenuated cosine wave with a frequency of 20 kHz, , which was our message signal, as the demodulated signal. The attenuation increases on increasing the message signal frequency or decreasing the filter cut-off frequency.

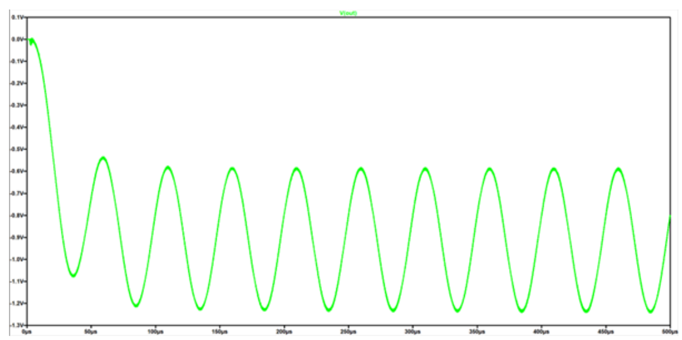

Fig. 12. Simulated Output after Demodulation

E. Hardware Results

Figure 13 shows the outputs of the switching modulator as well as the demodulator when a 10 kHz sinusoidal signal is taken as the message signal. We can observe that the modulated signal is a high frequency signal which has a shape corresponding to the message signal. The high frequency sine wave received as an output of the Colpitts oscillator is used to perform this modulation. On passing this modulated signal through the low-pass filter, we get back the sinusoidal signal having the same frequency as the message signal.

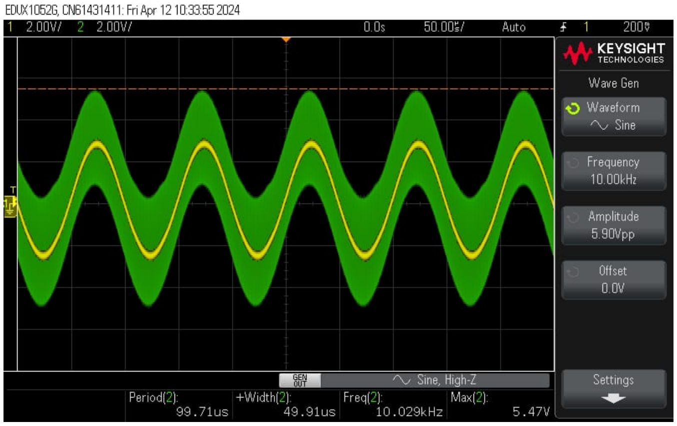

Fig. 13. Modulator output (in green) and Demodulator output (in yellow) for a 10 kHz sinusoidal message signal

Figure 14 shows the outputs of the switching modulator as well as the demodulator when a 10 kHz ramp signal is taken as the message signal. We can observe that the modulated signal has the shape and frequency same as that of the message signal.

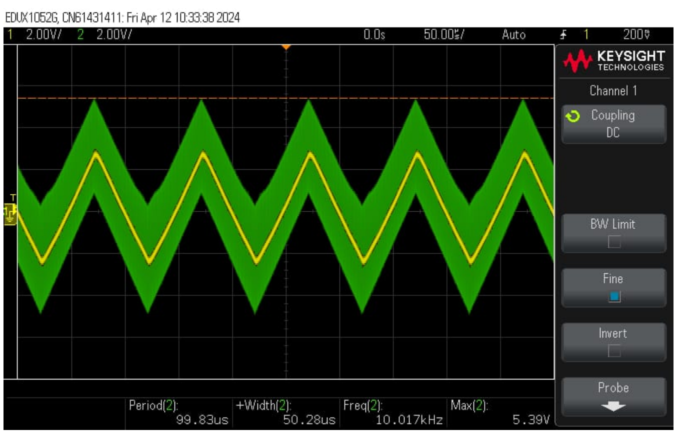

Fig. 14. Modulator output (in green) and Demodulator output (in yellow) for a 10 kHz ramp message signal

Figure 15 shows the outputs of the switching modulator as well as the demodulator when a 10 kHz square wave is taken as the message signal. We can observe that the modulated signal is of the shape of a square signal and its frequency matches that of the message signal.

F. Advantages of Colpitts Oscillator

The Colpitts oscillator has various advantages over other types of oscillators. Some of them are mentioned below:

1) It can generate sinusoidal signals of very high frequencies.
2) Its circuit is very simple and easy to implement.
3) It can withstand low and high temperatures.
4) It has a high frequency stability over time.

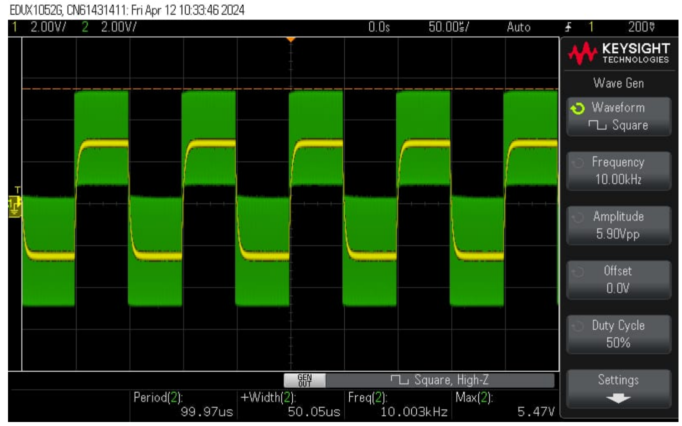

Fig. 15. Modulator output (in green) and Demodulator output (in yellow) for a 10 kHz square wave message signal

5) It produces a purer sinusoidal waveform compared to other oscillators due to the low impedance paths of the capacitors at high frequencies.

G. Challenges

While designing and making the circuit of Colpitts oscillator, we faced the following challenges:

1) The range of values of inductor available is very limited hence we cannot vary its frequency much.
2) Colpitts oscillator is majorly meant to produce high frequencies. Hence, it is very difficult to generate a low frequency sine wave using it.
3) Electronic devices like Op-Amps, BJTs and MOSFETs work only at low frequencies. Hence, they cannot be used to implement any application of Colpitts oscillator. The only device that can be used is a diode.

III. Conclusion

The Colpitts Oscillator is a widely used and easy-to-implement oscillator which has many applications such as generating clock for microprocessors, RF communication, local oscillators and audio oscillators.