Lock-In Amplifier

Introduction

A lock-in amplifier is an analog instrument designed to extract a specific signal from a noisy background. It does this by using a reference signal at the same frequency as the signal of interest. Lock-in amplifiers are invaluable in various scientific and engineering applications, especially when dealing with signals that are weak and buried in noise.

Block Diagram of Full System

The system comprises several key components:

1. **Microphone and Amplifier**
2. **LED and Photodiode**
3. **Modulator and Demodulator**
4. **Low-Pass and Band-Pass Filters**
5. **Input and Output amplifier**

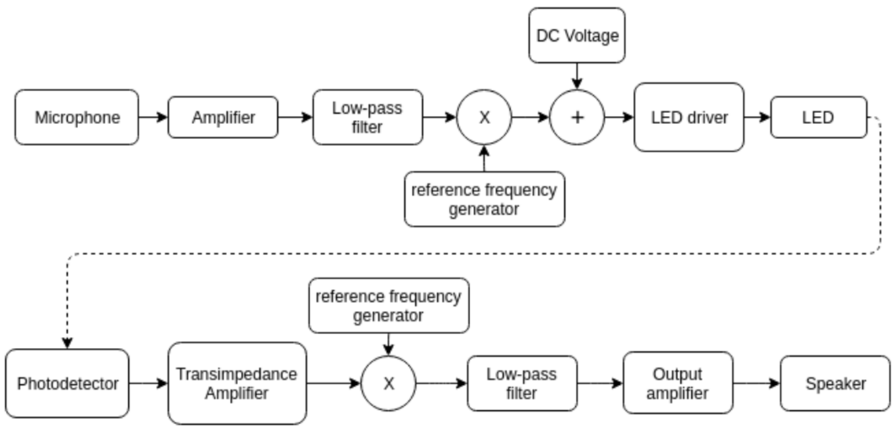

Figure 1: Block Diagram of Full System

Components and Design

Inverting Amplifier

An inverting amplifier with a gain of 180 is used to amplify the input signal from the microphone. The input voltage V_{in} is approximately 100 mV peak-to-peak with a frequency range of 20 Hz to 20 kHz.

$$\frac{V_0}{V_{in}} = -\frac{R_f}{R_1}$$

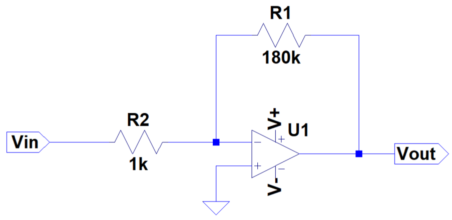

Figure 2: Input Amplifier of gain 180

Low-Pass Filter

The low-pass filter, implemented using the Sallen-Key topology, is designed to pass signals with frequencies lower than a specified cutoff frequency and attenuate signals with frequencies higher than the cutoff frequency.

The transfer function for a Sallen-Key low pass filter is given by:

$$H(s) = \frac{k}{s^2(R_1R_2C_1C_2)+s(R_2C_2+R_1C_2+(1-k)R_1C_1)+1}$$

For a Butterworth response, we have:

$$R_1 = R_2 = R\,, \quad C_1 = C_2 = C$$

The cutoff frequency, f_c is given by $\frac{1}{2\pi RC} = 20Khz$. If we let $R = 10K\Omega$, then $C = 0.8nF$.
However, these values didn't result in significant attenuation. As a result, we adjusted the cutoff frequency to $15Khz$, which gives $C = 1nF$.

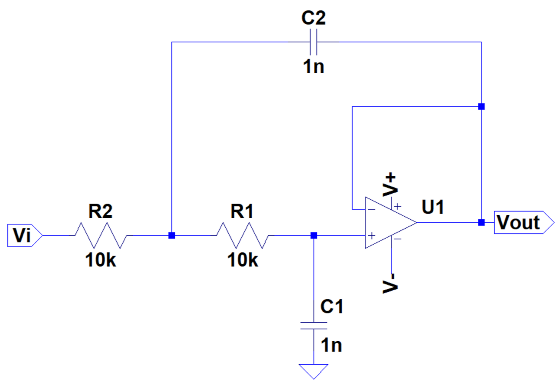

Figure 3: Sallen Key Lowpass Filter

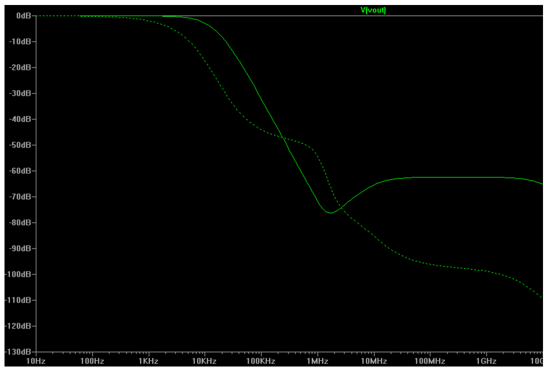

Figure 4: output of Low pass filter

Modulation

The modulation process involves multiplying the signal by a clock pulse using a switching circuit and then using a low-pass filter to extract the desired frequency component. For instance, a band-pass filter can be created using a low-pass filter of order 9 and a high-pass filter of order 8 to achieve a sharp roll-off.

A) Current Switcher

In the case of a switching circuit, the principle applied for the current switcher mirrors that of a Gilbert cell.

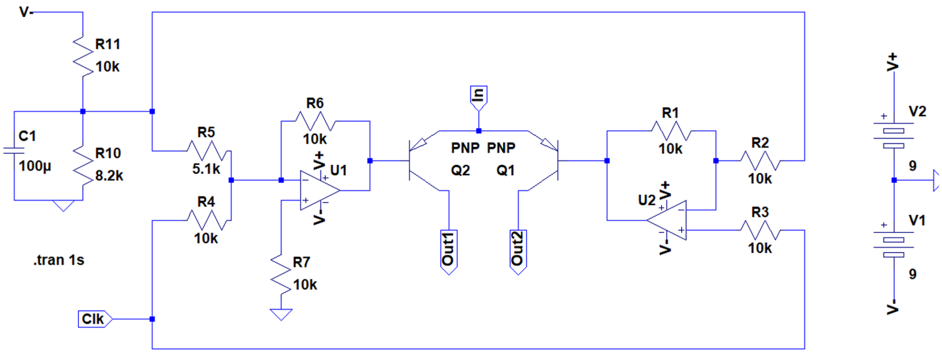

Figure 5: Current switcher

In current switcher, if V1 substantially exceeds V2, the entire current is channeled through BJT2, leaving BJT1 with none. On the other hand, if V1 is considerably lower than V2, all the current goes through BJT1, leaving BJT2 devoid of any.

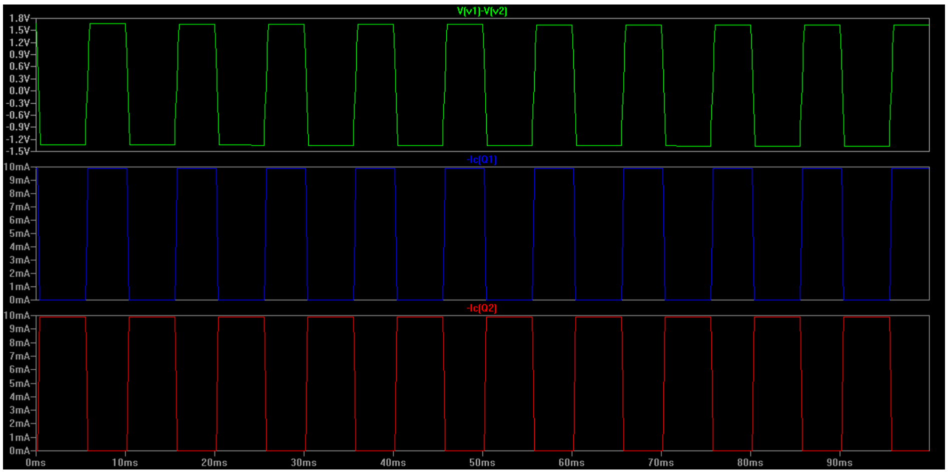

Figure 6: Output when input is DC current

The output we get from our current switcher is a modulated signal. This is the result of the input signal being multiplied by the square wave generated from the clock pulse. This process shifts the frequency spectrum of the input signal to match the frequency of the clock pulse. So, if we input a sinusoidal wave, what we end up with at the output is a signal that's been multiplied by the clock pulse.

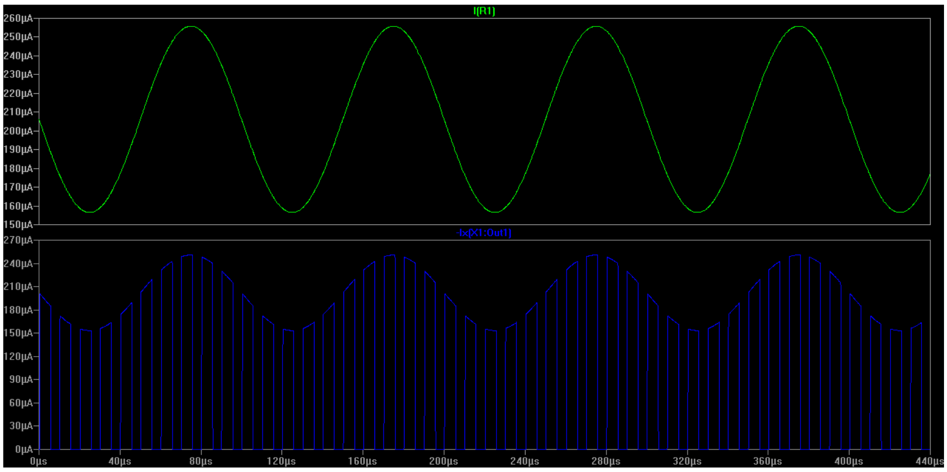

Figure 7: Output when input is AC current

B) Band-Pass Filter

Band Pass Filter: Low frequency = 90 kHz, High frequency = 110 kHz
The band-pass filter is crucial for isolating the desired signal frequency from other frequencies. The design involves both low-pass and high-pass filters:

$H_{BP}(s) = H_{HP}(s) \cdot H_{LP}(s)$

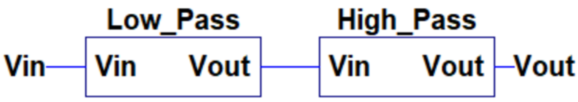

Figure 8: Band Pass Filter combining Low pass and High Pass filters

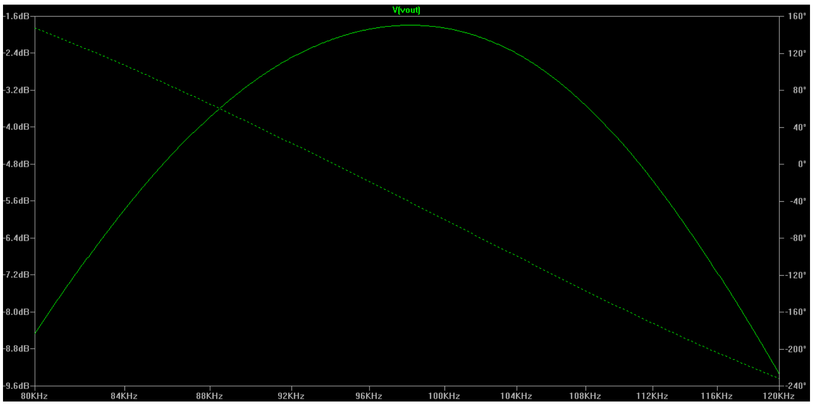

Figure 9: Output of Band Pass Filter

- **Low-Pass Filter**

  The lock-in amplifier's low pass filter is designed to allow signals with a frequency lower than a certain cutoff frequency to pass, while attenuating frequencies above the cutoff. This filter is designed using the Sallen-Key topology and is a 9th order low-pass filter.
  For a cutoff frequency of
  $110Khz$, and a resistance, R, of $10k\Omega$

  $C = \frac{1}{2\pi \cdot 110 \cdot 10 \cdot 10^3 \cdot 10^3} = 144\,\text{pF}.$

  We then calculate the specific capacitances using the following factors:

  $C_1 = 5.758 \times 144pF = 829.152pF$

  $C_2 = 0.1736 \times 144pF = 25pF$

  $C_3 = 2 \times 144pF = 288pF$

  $C_4 = 0.5 \times 144pF = 72pF$

  $C_5 = 1.305 \times 144pF = 187.92pF$

  $C_6 = 0.7661 \times 144pF = 110pF$

  $C_7 = 1.455 \times 144pF = 210pF$

  $C_8 = 1.327 \times 144pF = 191.1pF$

  $C_9 = 0.517 \times 144pF = 74.45pF$

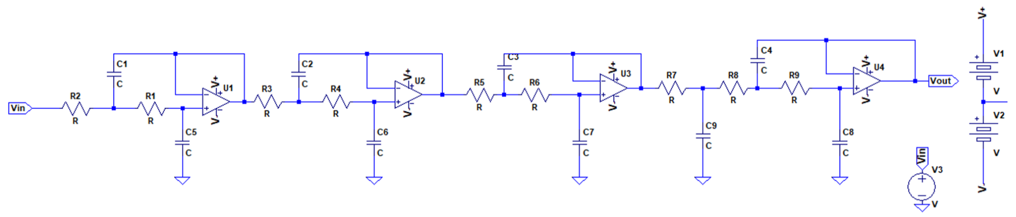

Figure 10: Low pass filter of order 9

- **High-Pass Filter**

  The high pass filter section is designed to block low frequencies and allow high frequencies to pass. The filter design follows the Sallen-Key topology, low-pass filter of order 8.

  For a cutoff frequency of $90Khz$, and $C = 0.5nF$,

  $R = \frac{1}{2\pi \cdot 90 \cdot 10^3 \cdot 0.5 \cdot 10^-9} = 3.537\ K\Omega$

  We then calculate the specific resistances using the following factors:

  $R_1 = 3.537/5.125K\Omega = 690\Omega$

  $R_2 = 3.537/0.195K\Omega = 18.12K\Omega$

  $R_3 = 3.537/1.8K\Omega = 1.964K\Omega$

  $R_4 = 3.537/0.5557K\Omega = 6.36K\Omega$

  $R_5 = 3.537/1.202K\Omega = 3K\Omega$

  $R_6 = 3.537/0.843K\Omega = 4.25K\Omega$

  $R_7 = 3.537/1.020K\Omega = 3.5K\Omega$

  $R_8 = 3.537/0.9809K\Omega = 3.6K\Omega$

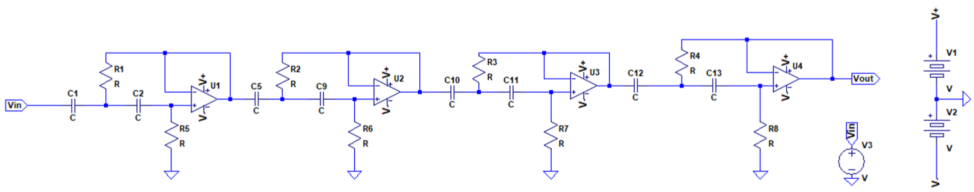

Figure 11: High Pass Filter of order 8

To determine the values of R and C, we utilize the following reference tables:

Order, n	C_1 / C or R/R_1	C_2 / C or R / R_2	C_3/C or R/R_3
	1.455	1.327	0.5170
9	1.305	0.7661	
	2.000	0.5000	
	5.758	0.1736	

Table 1: For Low Pass Filter

Order, n	C_1 / C or R/R_1	C_2 / C or R / R_2	C_3/C or R/R_3
	1.020	0.9809	
8	1.202	0.8313	
	1.800	0.5557	
	5.125	0.1950	

Table 2: For High Pass Filter

C) Modulator Circuit

The modulator circuit drives an LED using a transconductance amplifier. An inverting summing amplifier is used to properly bias the LED, ensuring the peak-to-peak brightness variation is maximized and the average brightness is as high as possible for optimal communication distance.

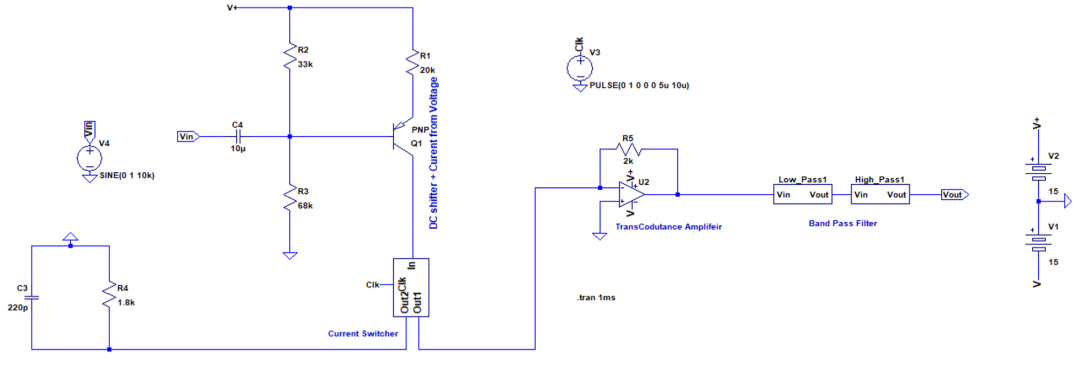

Figure 12: Modulator Circuit integrating current switcher and Band Pass filter

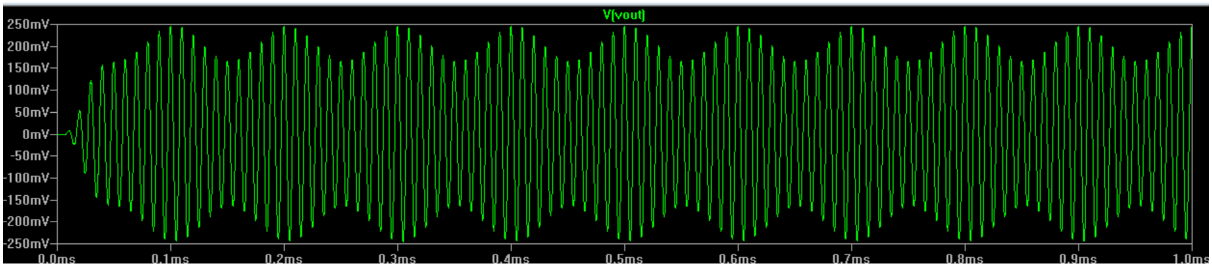

Figure 13: Modulator Output

- FFT Analysis

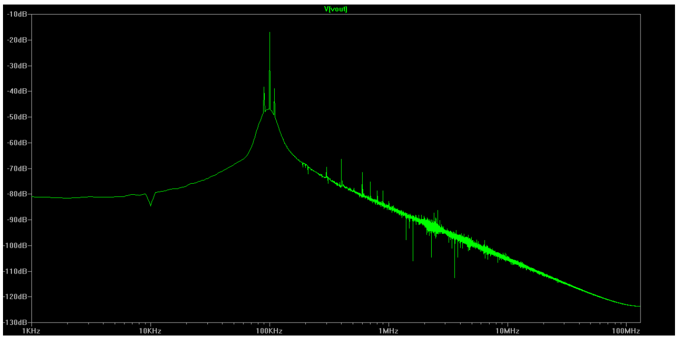

Figure 14: FFT analysis of Modulator Circuit

LED and Photodiode

The system uses an LED and a photodiode to transmit data over a light channel. The LED is driven by a transconductance amplifier, while a transimpedance amplifier converts the current signal from the photodiode back into a voltage signal.

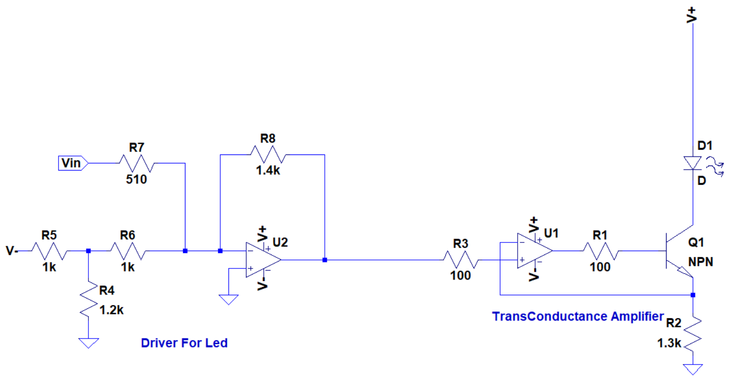

Figure 15: Transconductance Amplifier used to drive LED

As Lt spice Doesn't have built in photodiode, I am using current controlled Current source for LT spice model

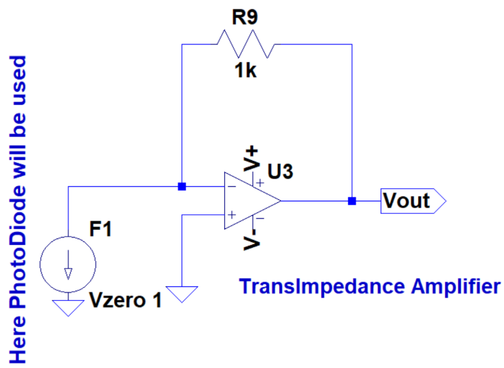

Figure 16: Transimpedance Amplifier used after photodiode

Demodulation

The demodulation process uses the same technique as modulation. The input is passed through a band-pass filter with cutoff frequencies of 35 kHz and 250 kHz. Another band-pass filter with cutoff frequencies of 20 Hz and 20 kHz extracts the audio signal centered around zero by the demodulating mixer.

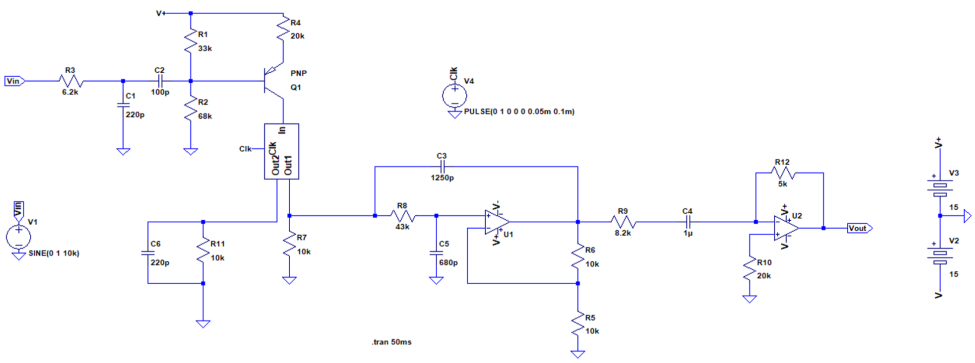

Figure 17: Demodulator Circuit

System Integration and Testing

The entire system was integrated and tested in stages. Each component was tested individually before the final integration. The performance was evaluated based on the signal-to-noise ratio and the ability to extract the desired signal from the noisy environment.

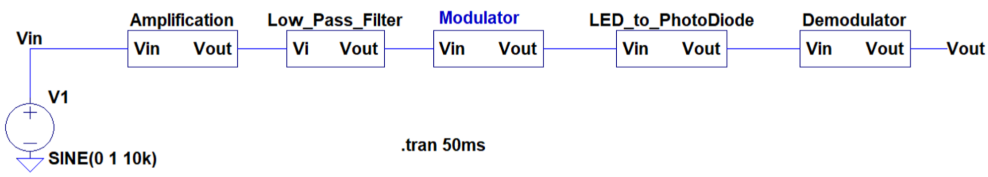

Figure 18: Final Integrated System

Performance and Noise Analysis

The lock-in amplifier demonstrated excellent performance in extracting weak signals from noise. The noise analysis revealed that the system effectively rejected unwanted frequencies and amplified the signal of interest. Due to low Pass filter the output waveform is shifted.

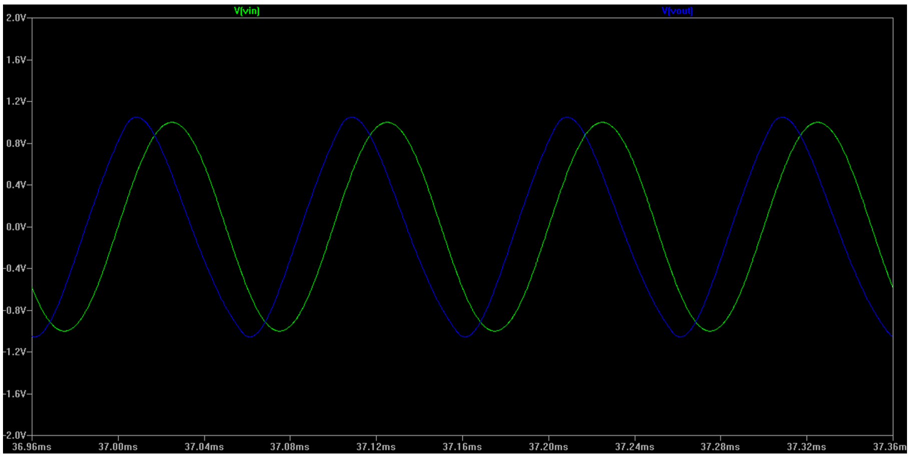

Figure 19: Output of Lock-in Amplifier

Conclusion

Lock-in amplifiers are powerful tools for signal extraction in noisy environments. By carefully designing and integrating each component, a highly effective system was developed to transmit and receive audio signals through amplitude-modulated light. Future work could explore frequency modulation and other enhancements to further improve the system's performance.

References

- Analog Devices: A Beginner's Guide to Filter Topologies
- ResearchGate: Design of Butterworth Band-Pass Filter
- All the schematics for Lock in Amplifier: Lock In amplifier.zip