Lab Assignment 2

E. Mihir Divyansh[a] and Manoj Kumar Ambatipudi[b]

[a]*EE23BTECH11017, BTech 2nd Year, Electrical Engineering*
[b]*EE23BTECH11040, BTech 2nd Year, Electrical Engineering*

Dr. Gajendranath Chaudury

Contents

1. Introduction

This is the lab report for Assignment 2, to understand a PN junction diode. First, we plot the $I-V$ characteristics of PN junction and Zener diodes in forward and reverse bias. Next, we use an Op-Amp to create a zero-cut rectifier for full-wave and half-wave rectifications. We then apply a filter to remove HF components from the signal. Finally, we analyze the spectrum of the input and output signals before and after filtering to understand the effects of each stage.

2. Equipment Used

- Diode - 1N4007 $\times 1$
- Zener Diode $\times 1$
- Op Amp - LM 741
- Resistors : 1kΩ, 10kΩ
- Capacitors : 470 μF
- Inductors : 1mH

3. Theory

3.1. Diodes

Diodes are semiconductor devices that allow current to flow in only one direction. They are formed by joining a p type semiconductor (with excess holes) and an n type semiconductor (with excess electrons). Diodes are used in a wide range of electronic circuits, including:

- Power supplies
- Logic gates
- Switching circuits
- LED lighting

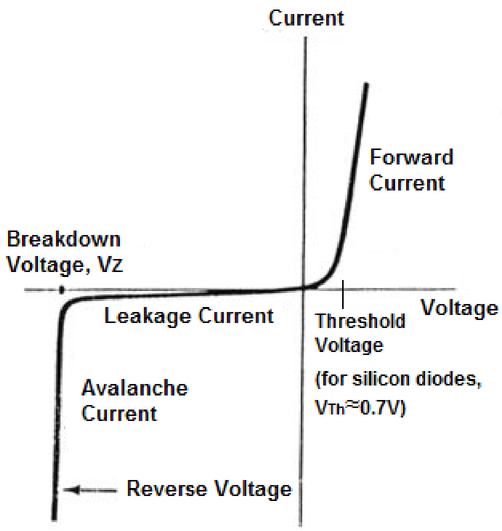


Figure 1. I-V characteristics of a diode

3.2. Rectifiers

Rectifiers are electrical circuits made primarily for converting AC to DC.

Types of Rectifiers

1. Half Wave Rectifier
2. Full Wave Rectifier
3. Bridge Rectifier
4. Voltage Doubler Rectifier

A rectifier almost always consists of a diode to control the flow of current. An example can be the following.

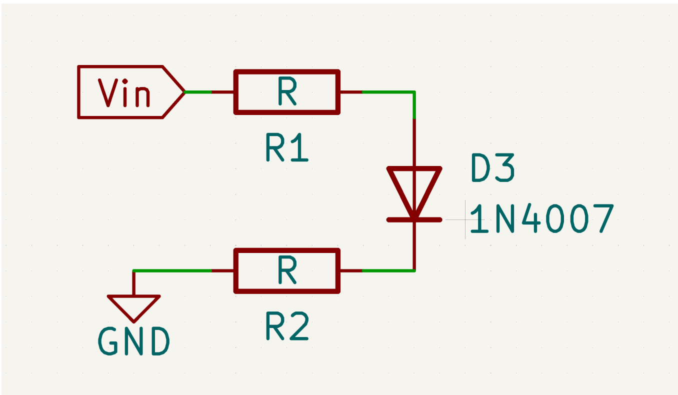


Figure 2. Schematic of a simple Half Wave rectifier

In the above example, if the input voltage is an A sine wave, the positive part of the cycle, $\geq 0.7V$ is allowed to pass through. The graph may look like this.

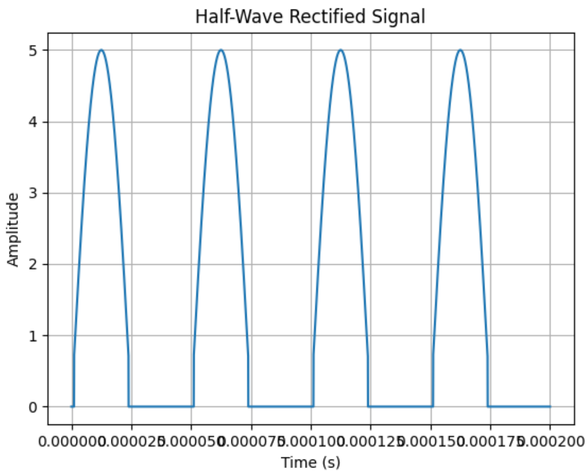


Figure 3. Half Wave Rectified signal

A full wave rectifier is built by using 4 diodes in the following manner:

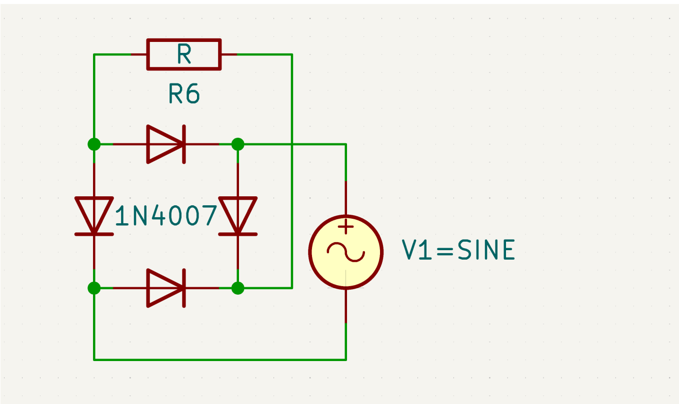


Figure 4. Bridge wave circuit

The output of this circuit may look like

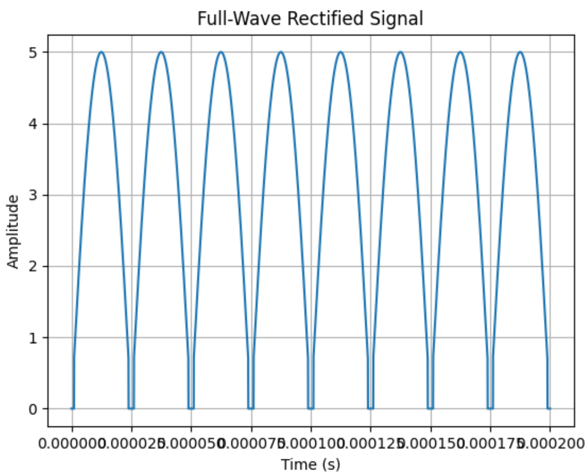


Figure 5. Full Wave Rectified signal

3.3. Op Amp Adder

An Op-Amp is a voltage amplifier with a differential input, usually a single output and a very high gain. The basic principle of the working of an Op-Amp is

$$V_o = A(V_+ - V_-) \tag{1}$$

One of the uses of an Op-Amp is to construct circuits that perform Arithmetic operations. An adder adds the input signals and scales it in some manner to give output.

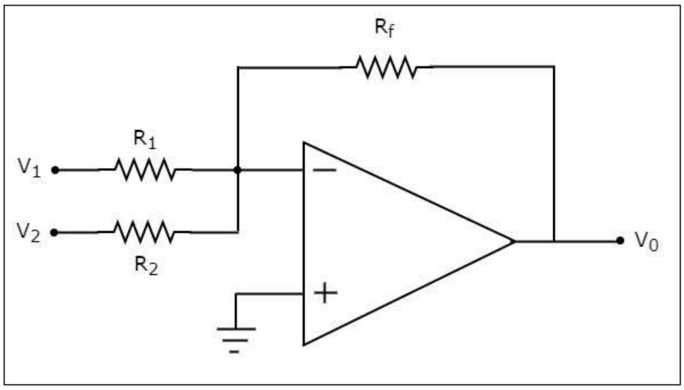


Figure 6. Op-Amp Adder

It uses the principle of superposition and the high gain of the op-amp to produce an output voltage that is the weighted sum of the input voltages.

The basic circuit for an op-amp adder is shown in Figure 6. The circuit consists of an op-amp in an inverting configuration with 2 input resistors.

3.3.1. Mathematical Analysis

In the inverting adder configuration, the output voltage V_0 is given by the weighted sum of the input voltages V_1, V_2 as follows:

$$V_{\text{out}} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2\right)$$

Where:

- R_f is the feedback resistor.
- R_1, R_2 are the input resistors corresponding to the input voltages V_1, V_2.
- V_0 is the output voltage.

This equation assumes that the op-amp is ideal, meaning that:

- The open-loop gain is infinite.
- The input impedance is infinite.
- The output impedance is zero.

For equal input resistors $R_1 = R_2 = R_{\text{in}}$, the output voltage simplifies to:

$$V_{\text{out}} = -\frac{R_f}{R_{\text{in}}}(V_1 + V_2)$$

If the input resistors are all equal to the feedback resistor R_f, the output voltage is simply the negative sum of the input voltages:

$$V_{\text{out}} = -(V_1 + V_2)$$

3.3.2. Why is this useful?

A diode takes a minimum voltage of 0.7 V before it starts conducting. Therefore, in half-wave and full-wave rectifiers, the input signal effectively starts after 0.7 V. However, in many applications, we are interested in zero-cut rectifiers, where the signal is rectified without any voltage offset.

To achieve this, we can use an op-amp adder to offset the input signal by 0.7 V. By adding a 0.7 V offset to the input signal, the output of the adder becomes:

$$V_{\text{offset}} = V_{\text{in}} + 0.7\,\text{V}$$

This offset input voltage is then fed into the rectifier circuit. The diode will now conduct when the original input signal exceeds 0 V (after the offset), effectively creating a zero-cut rectifier. The input signal for a normal rectifier is offset and input to 2

The design used for this lab is shown here

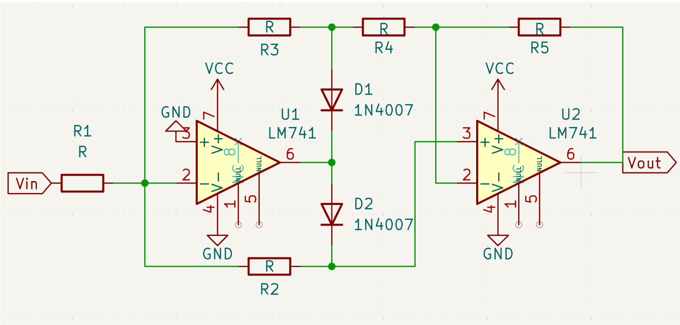


Figure 7. Full Wave Rectifier with Op-Amp

3.4. Filters

Filters are electrical circuits meant to allow or stop certain frequencies. They can be made of any combinations of R, L and C. Filters play a crucial role in signal processing, communication systems, and many other electronic applications.

3.4.1. Types of Filters

There are several types of filters, each designed to target specific frequency ranges:

- **Low-Pass Filter (LPF):** Allows frequencies below a certain cutoff frequency to pass through while attenuating higher frequencies. This type of filter is often used to remove high-frequency noise from a signal.
- **High-Pass Filter (HPF):** Allows frequencies above a certain cutoff frequency to pass through while attenuating lower frequencies. It is commonly used to block low-frequency interference.
- **Band-Pass Filter (BPF):** Allows frequencies within a specific range (band) to pass through while attenuating frequencies outside this range. Band-pass filters are useful in applications like radio communications, where a specific frequency band needs to be isolated.
- **Band-Stop Filter (BSF) or Notch Filter:** Attenuates frequencies within a specific range while allowing frequencies outside this range to pass through. Notch filters are often used to eliminate a specific unwanted frequency, such as 50/60 Hz power line interference.
- **All-Pass Filter:** Allows all frequencies to pass through but alters the phase relationship between various frequencies. All-pass filters are used in phase correction and signal processing applications.

3.4.2. Filter Design Using R, L, and C

The design of filters using resistors, inductors, and capacitors can be approached in various ways depending on the desired filter type and characteristics:

- **RC Filters:** These are the simplest types of filters, constructed using resistors and capacitors. An RC low-pass filter, for example, consists of a resistor in series with a capacitor. The cutoff frequency f_c is determined by the values of the resistor R and capacitor C:

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

- **RL Filters:** These filters use resistors and inductors. An RL high-pass filter, for example, can be constructed with a resistor in parallel with an inductor. The cutoff frequency f_c is given by:

$$f_c = \frac{R}{2\pi L}$$

- **LC Filters:** Inductors and capacitors are often used together to create more complex filters, such as band-pass and band-stop filters. The resonance frequency f_0 of an LC circuit, which is used in band-pass and band-stop filters, is determined by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

- **RLC Filters:** Combining resistors, inductors, and capacitors allows for precise control over the frequency response. An RLC circuit can be designed to provide a specific bandwidth and quality factor Q, which defines the sharpness of the filter's response.

$$Q = \frac{f_0}{\Delta f}$$

Where Δf is the bandwidth around the resonance frequency f_0.

3.4.3. Applications of Filters

Filters are used in a wide range of applications, including:

- **Signal Conditioning:** Filters are used to remove unwanted noise or excess harmonics from signals, making them cleaner for further processing.
- **Audio Processing:** In audio systems, filters shape the frequency response to achieve desired sound characteristics, such as bass and treble control.
- **RF Applications:** Filters are crucial in RF systems for selecting or rejecting specific frequency bands, such as in tuners and transmitters.
- **Power Supplies:** Filters are used to smooth out ripples in DC power supplies, ensuring a steady output voltage.
- **Communication Systems:** Filters are used to separate different channels in communication systems, enabling multiplexing and demultiplexing of signals.

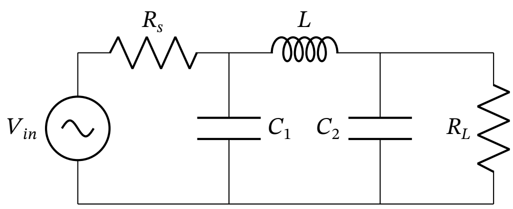
3.4.4. Using filters after rectification.

There are multiple reasons for filtering after building the rectifier.

- To remove higher harmonics
- To isolate the DC component
- To achieve a specific signal shape or characteristic

3.5. Filter Design for this experiment

The filter that was chosen for this project was an LC based filter.



The Π filter shown in Figure 3.5 was chosen for the experiment. It behaves as a ____ filter. The transfer function for the filter is calculated as follows

$$G(s) = \frac{V_{out}}{V_{in}} = \frac{V_{C_2}}{V_{in}}$$
$$= \frac{R_L}{R_L R_s C^2 L s^3 + (R_L LC + R_s LC)\, s^2 + (2R_L R_s C + L)\, s + (R_L + R_s)} \tag{2}$$

When R_s and R_L are ideal, the equation simplifies to

$$G(s) = \frac{1}{LCs^2 + 1} \tag{3}$$

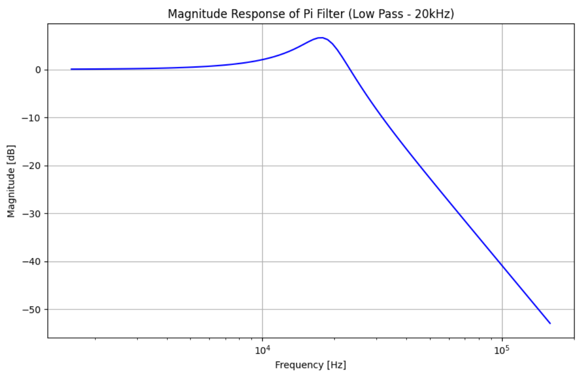


Figure 8. Frequency Response of the filter

Phase response for this system is as follows.

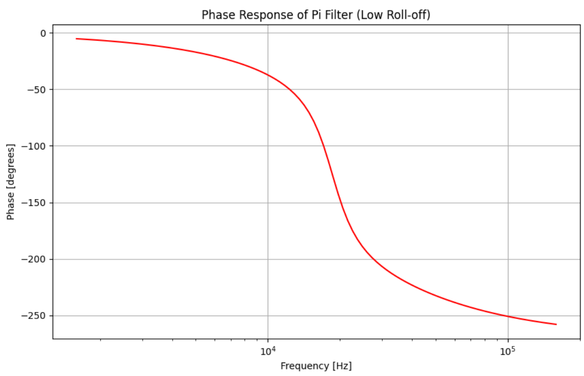


Figure 9. Phase Response of the filter

4. Fourier Series And the Frequency domain

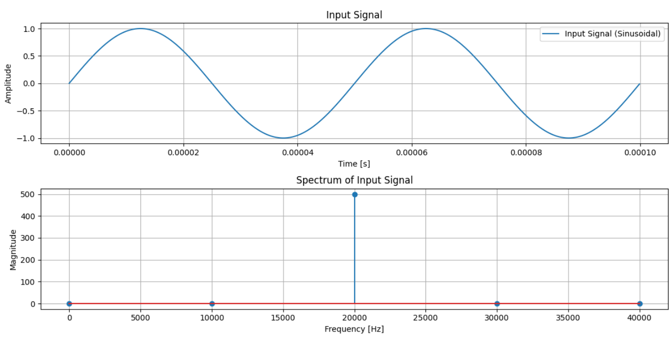


Figure 10. Sine Wave And It's Spectrum

The Fourier series of a periodic function $f(t)$ with period T can be expressed as:

$$f(t) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos \frac{2\pi n t}{T} + b_n \sin \frac{2\pi n t}{T} \right)$$

where the Fourier coefficients a_0, a_n, and b_n can be calculated. Here,

$$f(t) = \begin{cases} A\sin(\omega t) & 2n\pi \le \omega t < (2n+1)\pi \\ 0 & \text{else} \end{cases}$$

4.0.1. DC Component

The DC component or the average value of the function is given by:

$$\begin{aligned} a_0 &= \frac{1}{T} \int_0^T f(t), dt \\ &= \frac{A\omega}{2\pi} \left(\int_0^{\frac{\pi}{\omega}} \sin(\omega t)\, dt + \int_{\pi}^{2\pi} 0\, dt \right) \\ &= \frac{A}{\pi} \end{aligned}$$

4.0.2. Cosine Coefficients

The real coefficients are calculated as:

$$\begin{aligned} a_n &= \frac{2A}{T} \int_0^T f(t) \cos \frac{2\pi n t}{T}\, dt \\ &= \frac{2\omega A}{2\pi} \int_0^{\frac{\pi}{\omega}} \sin(\omega t) \cos\left(\frac{2\pi n \omega t}{2\pi}\right) dt \\ &= \frac{\omega A}{\pi} \int_0^{\frac{\pi}{\omega}} \sin(\omega t) \cos(n\omega t)\, dt \end{aligned}$$

Using the trigonometric identity

$$\sin(\omega t)\cos(n\omega t) = \frac{1}{2}\left(\sin(\omega(n+1)t) - \sin(\omega(n-1)t)\right)$$

We get

$$\begin{aligned} a_n &= \frac{2A}{\frac{2\pi}{\omega}} \int_0^{\frac{\pi}{\omega}} \frac{A}{2} \left(\sin(\omega(n+1)t) - \sin(\omega(n-1)t)\right) dt \\ &= \frac{A}{2\pi} \left[-\frac{1}{n+1} \cos(\omega(n+1)t) + \frac{1}{n-1} \cos(\omega(n-1)t) \right]_0^{\frac{\pi}{\omega}} \\ a_n &= \frac{A}{\pi} \frac{1+\cos(\pi n)}{1-n^2}, \quad n > 1 \end{aligned} \tag{4}$$

For $n = 1$,

$$a_1 = 0$$

Therefore

$$a_n = \begin{cases} \frac{A}{\pi} & n = 0 \\ 0 & n = 1 \\ \frac{A}{\pi} \frac{1+\cos(\pi n)}{1-n^2} & \text{else} \end{cases}$$

4.0.3. Sine Coefficients

The sine (or imaginary) coefficients are calculated as:

$$\begin{aligned} b_n &= \frac{2}{T} \int_0^T f(t) \sin\left(\frac{2\pi n t}{T}\right) dt \\ &= \frac{A\omega}{\pi} \int_0^{\frac{\pi}{\omega}} \sin(\omega t) \sin(n\omega t)\, dt \\ &= \frac{A\omega}{\pi} \int_0^{\frac{\pi}{\omega}} \frac{1}{2} \left(\cos(\omega(n-1)t) - \cos(\omega(n+1)t)\right) dt \end{aligned}$$

For $n = 1$,

$$b_1 = \frac{A}{2}$$

For $n > 1$, $b_n = 0$

This can be verified by plotting the spectrum of the waves.

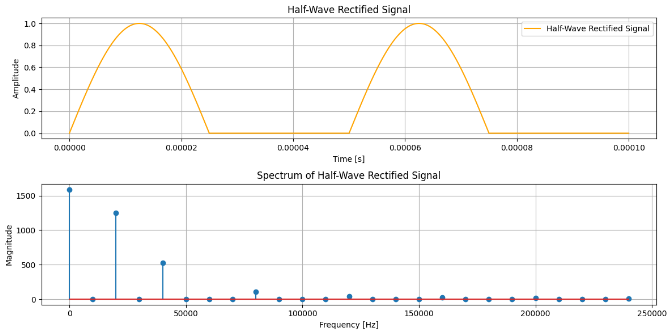


Figure 11. Half Wave And It's Spectrum

4.1. For a full wave rectifier

The full-wave rectified sine wave can be expressed as:

$$f(t) = |A\sin(\omega t)|$$

4.1.1. DC Component

$$a_0 = \frac{1}{T}\int_0^T |A\sin(\omega t)|\, dt$$

The period of the function is π radians:

$$a_0 = \frac{\omega}{\pi}\int_0^{\frac{\pi}{\omega}} A\sin(\omega t)\, dt$$

Evaluating the integral:

$$a_0 = \frac{A\omega}{\pi}\left(-\frac{1}{\omega}\cos(\omega t)\right)_0^{\frac{\pi}{\omega}}$$

$$a_0 = \frac{2A}{\pi}$$

4.1.2. Cosine Coefficients

$$a_n = \frac{2}{T}\int_0^T |A\sin(\omega t)|\cos\left(\frac{2\pi n t}{T}\right) dt$$

For a full-wave rectified sine wave:

$$a_n = \frac{2\omega A}{\pi}\int_0^{\frac{\pi}{\omega}} \sin(\omega t)\cos(n\omega t)\, dt$$

Using the identity

$$\sin(\omega t)\cos(n\omega t) = \frac{1}{2}\left(\sin((n+1)\omega t) - \sin((n-1)\omega t)\right) \tag{5}$$

$$a_n = \frac{A\omega}{\pi}\int_0^{\frac{\pi}{\omega}} \frac{1}{2}\left(\sin((n+1)\omega t) - \sin((n-1)\omega t)\right) dt$$

Evaluating the integral:

$$a_n = \frac{-A}{\pi}\left(\frac{\cos((n+1)\omega t)}{n+1} - \frac{\cos((n-1)\omega t)}{n-1}\right)_0^{\frac{\pi}{\omega}}$$

$$a_n = \frac{2A}{\pi}\frac{(-1)^n}{1-n^2}, \quad n \text{ is even}$$

$$a_n = 0, \quad n \text{ is odd}$$

4.1.3. Sine Coefficients

Since $f(t)$ is even:

$$b_n = 0 \quad \text{for all } n$$

1. **DC Component a_0:**

$$a_0 = \frac{2A}{\pi}$$

2. **Cosine Coefficients a_n:**

$$a_n = \begin{cases} \frac{2A}{\pi}\frac{1}{1-n^2}, & \text{if } n \text{ is even} \\ 0, & \text{if } n \text{ is odd} \end{cases}$$

3. **Sine Coefficients b_n:**

$$b_n = 0 \quad \text{for all } n$$

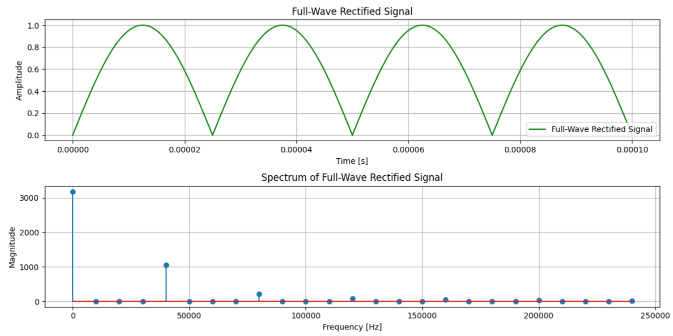


Figure 12. Full Wave And It's Spectrum

5. Observations

5.1. Diode Characteristics

The diode whose characteristics were measured is the 1N4007. It is a general purpose rectifier diode. In the experiment, we applied the voltage across the diode and a load resistor of $10k\Omega$, and the readings were taken. They are plotted as a scatter plot, and checked against ideal characteristics, calculated by the following

$$I = I_s\left(e^{\frac{V_d}{V_{ref}}} - 1\right), \quad \text{where } V_{ref} = \frac{nkT}{q}$$

Here n is the diode ideality factor, k is the Boltzmann constant, T is Temperature, and q is charge on an electron. The result of the experiment matches with the calculation as shown in Figure 13

To make the diode conduct from close to Zero volts, an op amp summer was used. The observations are shown in Figure 14

The reverse characteristics were then plotted for a Zener Diode shown in Figure 15.

The circuit designed for this purpose is a combination of Figure 6 and 7. The implementation is shown in Figure 17

5.1.1. Half Wave Rectifier

The data used for the plots is given in table 5.1.1

5.2. Rectifier

The output of this circuit for $V_{max} = 5V$ is shown below

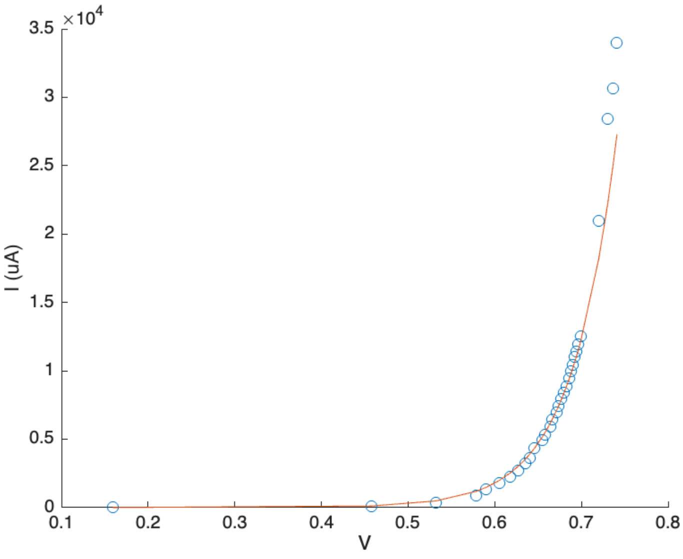


Figure 13. V-I characteristics of the diode - Calculation vs Observation

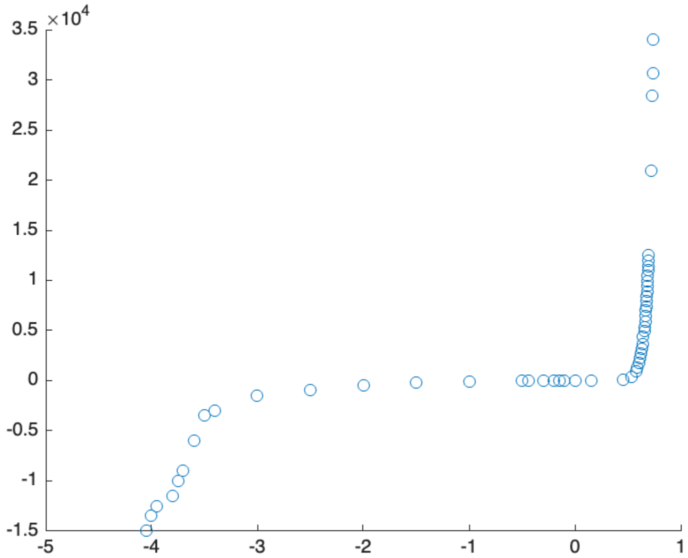


Figure 16. Complete V-I characteristics of a Zener diode

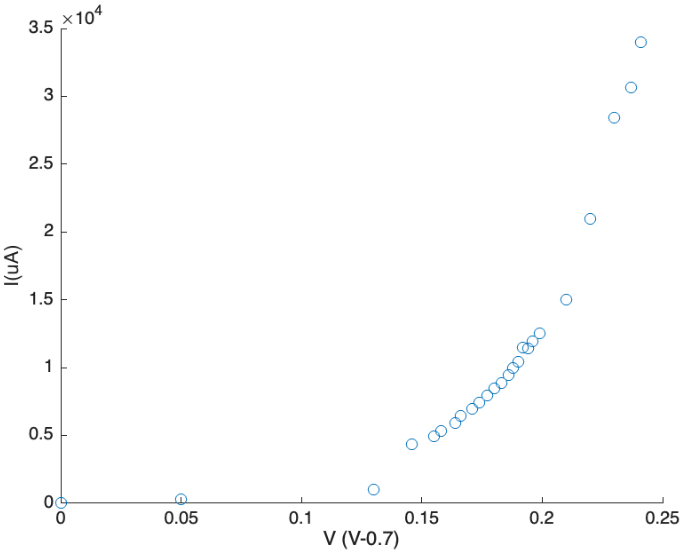


Figure 14. V-I characteristics of the diode - Offset

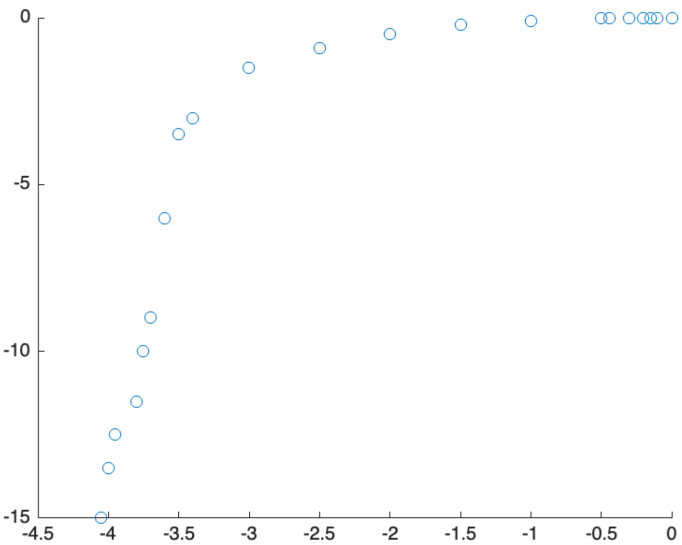


Figure 15. V-I characteristics of a Zener diode - Reverse Bias

Source Voltage	Diode Voltage (V)	Diode Current (μA)
0.2	0.159	0.1
0.5	0.458	80
1.0	0.532	369
1.5	0.579	885
2	0.59	1320
2.5	0.605	1769
3.0	0.618	2237
3.5	0.627	2715
4.0	0.635	3211
4.5	0.641	3650
5.0	0.646	4370
5.5	0.655	4950
6.0	0.658	5340
6.5	0.664	5900
7.0	0.666	6440
7.5	0.671	6960
8.0	0.674	7400
8.5	0.677	7940
9.0	0.68	8420
9.5	0.683	8890
10.0	0.686	9450
10.5	0.688	9950
11.0	0.69	10460
11.5	0.692	11000
12.0	0.694	11440
12.5	0.696	11950
13.0	0.699	12550
21.1	0.72	20950
28.1	0.73	28460
30.0	0.737	30660
33	0.741	34000

Table 1. Experimental Values

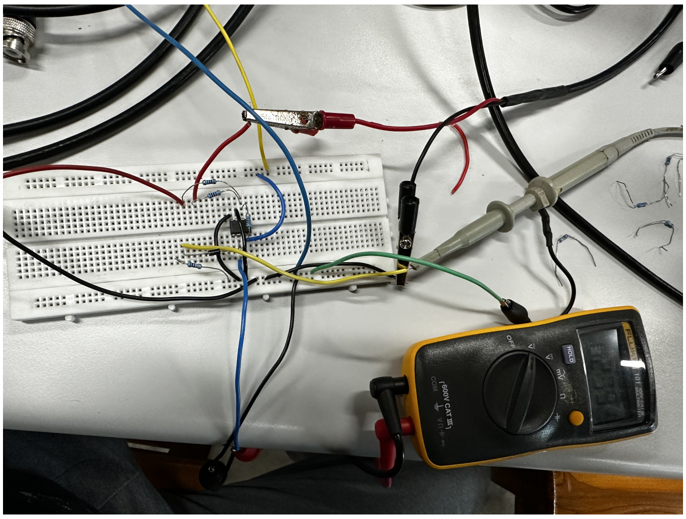


Figure 17. Circuit Built in the lab

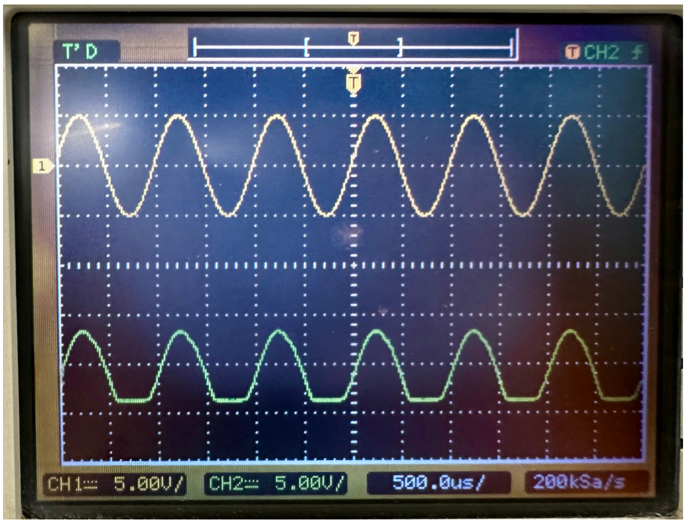


Figure 19. Output of the half wave rectifier for smaller signals.

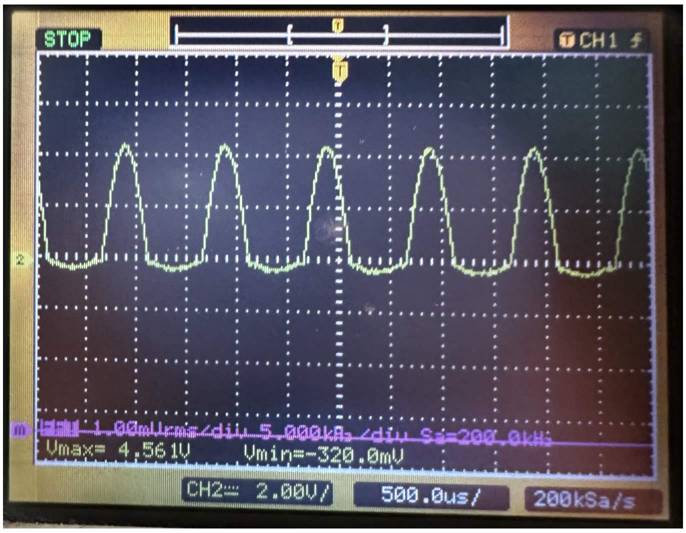


Figure 18. Output of the half wave rectifier for larger signals

There is distortion in the second half cycle because of diode breakdown (Due to Large Voltages).

For a smaller signal, the output is given in Figure 19

Figure 20. Output and Spectrum of Half Wave Rectifier.

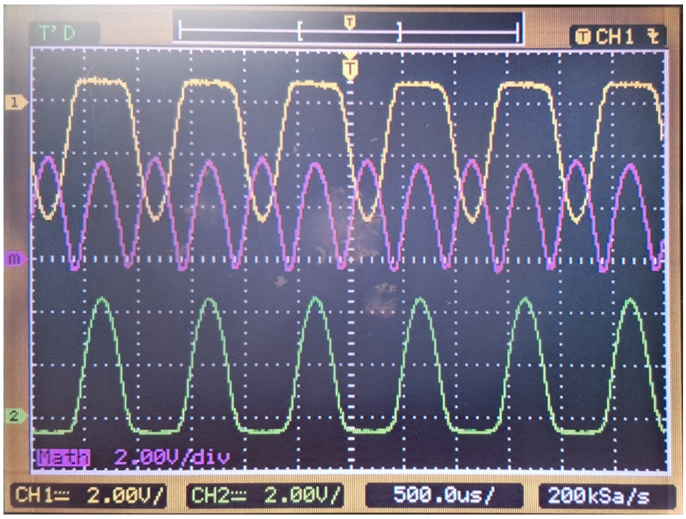


Figure 22. Output of the Bridge wave rectifier.

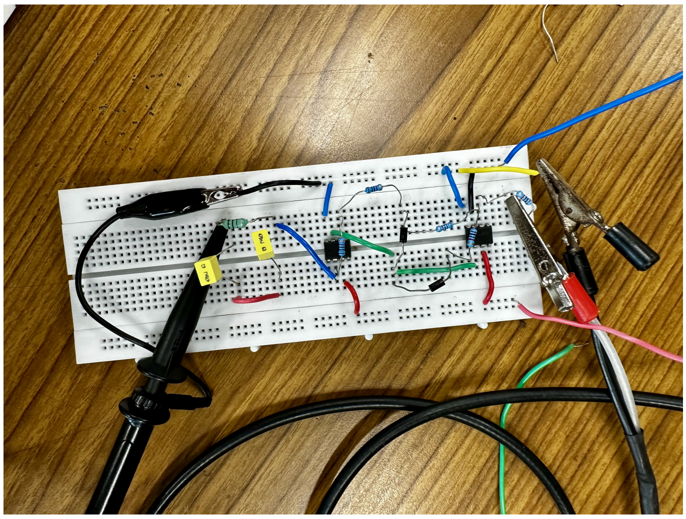


Figure 21. Full wave rectifier using an Op Amp.

5.2.1. Full Wave Rectifier

Without Op-Amp, A bridge wave rectifier can be built. The schematic shown in Figure 4 was followed. The voltage on either ends of the load resistor for a bridge rectifier is shown in Figure 20.

The difference was measured using Math on the oscilloscope. The output waveform is shown in Figure 22

Using the Op-Amp, the output was as follows

Figure 23. Output and Spectrum of the Full wave rectifier using an Op Amp.

The fourier coefficients can be calculated from the expressions derived in Section 4. For a Half wave rectified signal: This is corresponding to the half wave observed in Figure 20, and can be verified. The peak of the fundamental frequency occurs at $2V$, which is approximately where it is seen in the scope. The 2^{nd} harmonic has magnitude $\sim 0.8V$, which corresponds to $|a_2| = 0.849$

n	a_n	b_n
0	1.273	0.00
1	0.00	2.0
2	-0.849	0.00
3	0.00	0.00
4	-0.17	0.00
5	0.00	0.00
6	-0.073	0.00
7	0.00	0.00
8	-0.04	0.00
9	0.00	0.00

Table 2. Fourier Coefficients For A Half Wave Output

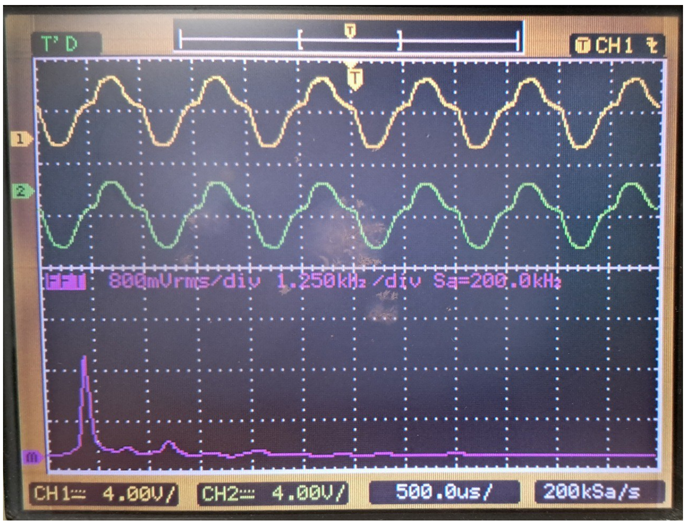


Figure 24. Output and Spectrum of the Half wave rectifier after Filter.

5.3. Filters

As discussed in section 3.5, The circuit constructed is shown in Figure 21. The output for a filtered half wave rectifier is shown in Figure 24. The 2nd Harmonic is seen to have significantly reduced, as expected. The coefficients can be calculated for the filtered output, by using the transfer function of the filter. (Not shown here)

Corresponding to Figure 23, the filtered output is shown here.

Figure 25. Output and Spectrum of the Full wave rectifier After Filter.

The filtered output has reduced n^{th} harmonics and can be seen.

A DC rectifier was also built by adding a simple capacitor to the output instead of the CLC filter. The Output of the rectifier for a input 7V signal is shown here.

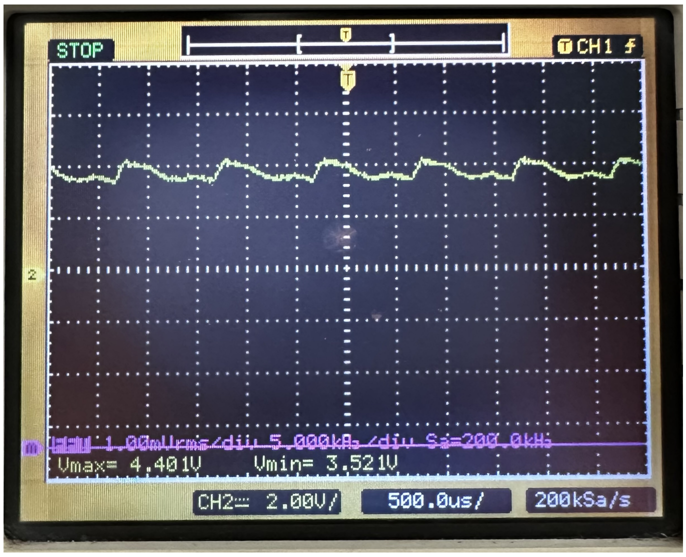


Figure 26. Output of a rectifier circuit with a connected capacitor.

The amplitude corresponds to the one calculated from Equation 4.1.1.

$$\frac{2A}{\pi} = \frac{14}{\pi} \sim 4.40V$$

This concludes the design and observation of the required circuits.

6. Sources of Error

The errors observed in the experiments can be largely attributed to the malfunctioning of the equipment used. Some other errors include

- Deviations in Outputs of the rectifiers
- Deiviation in Filter Behaviour and cutoff

7. Conclusion

In this lab report, we successfully explored the behavior and application of PN junction diodes, rectifiers, and filters. The experiments were designed to deepen our understanding of the I-V characteristics of diodes, the operation of different types of rectifiers, and the impact of filtering on signals.

Firstly, the I-V characteristics of the PN junction and Zener diodes were analyzed in both forward and reverse bias conditions. The observed results matched well with theoretical expectations, confirming the functionality and typical behavior of these diodes in various biasing scenarios.

Next, we constructed and tested half-wave and full-wave rectifiers. The resulting rectified signals were consistent with theoretical predictions, and the zero-cut feature effectively removed the offset, providing a cleaner DC output.

The application of a filter to the rectified signal was also done. An LC-based filter was used to remove high-frequency components, and the filtered output demonstrated the expected reduction in noise.

Finally, the analysis of the Fourier series and frequency domain characteristics of both half-wave and full-wave rectified signals showed the impact of rectification on the signal spectrum. The results illustrated the changes in the frequency content and the removal of harmonics.

Overall, the experiments successfully demonstrated the principles of diode operation, rectification, and filtering, providing practical insights into their applications in electronic circuits. The results obtained align with theoretical expectations.