Bilkent University

EEE-313

Lab 1

Photodiode and LED Characteristics

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Section 01

I. Introduction

The purpose of this lab is to observe the characteristics and working principles of light-emitting diodes (LED) and photodiodes. The circuit that is to be implemented is shown in Figure 1.

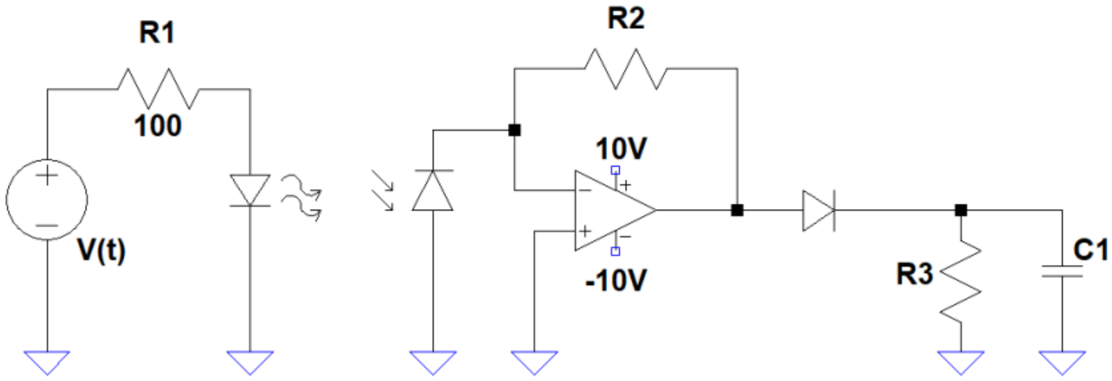

Figure 1: Circuit to be used in this lab

The circuit is expected to turn the induced current of the photodiode first into an AC voltage, then finally to a DC voltage. The current will be induced when the LED emits infrared radiation. pd333-3b/h0/l2 is used for the photodiode and SB-5010IRB is used for the LED. In addition to those, LM324 OPAMPs are also used to convert the photodiode current into an AC voltage. Finally, the envelope detector part with a 1N4001 diode, a resistor, and a capacitor is expected to convert the AC voltage into constant DC voltage at the output.

In this circuit, the LED and the photodiode are present. LEDs are essentially p-n junction diodes that emit light when electric current flows through them. When the current passes, the minority and majority charge carriers combine at the junction, and the energy is released as photons. In order to achieve this, the diode must be forward-biased [1]. The anode terminal is the positive side (which is the longer lead) and the cathode terminal is the negative side [1].

Photodiodes are devices that can detect photons (light) and if the energy of the photons detected is greater than the semiconductor material's energy gap, a current flow is observed. This is achieved by the generated electron-hole pairs inside the depletion region. After they are generated, the electrons are forced to move towards the n-side and the holes to the p-side by the electric field. This results in a current flow. The magnitude of the current depends on the light intensity. Unlike the LEDs, photodiodes operate under reverse bias [2].

For this circuit, the reason why 940 nm is chosen as the wavelength for this setup is that the LED (SB-5010IRB) and the photodiode (PD333-3B) operate the best at this wavelength as seen in their datasheets [3], [4]. They should also be placed with very little distance between them so that the radiation is detected by the photodiode. The distance should also be kept constant for reliable data. Choosing visible light for the LED also puts the setup at risk, since other external light sources can affect the experiment. Hence, 940 nm is chosen as the wavelength.

II. Hardware Implementation and Analysis

The circuit is to operate as follows: The input voltage V(t) = 3sin(2π*1000) is an AC voltage with 3V amplitude and 1 kHz frequency. According to the voltage across it, the LED will operate in the ON or OFF region. When it is ON, it will emit infrared radiation. This radiation will be detected by the photodiode and a current will be induced through it. The OPAMP will convert this current into an AC voltage and lastly, by the envelope detector circuit that contains a diode, a resistor, and a capacitor, this AC voltage will be converted to a DC voltage.

To set up the circuit, first R_2 value needs to be chosen so that the OPAMP is not saturated. Second, the values for C_1 and R_3 should be chosen such that constant DC voltage is obtained at the output.

- **Part A – R_2 Selection**

For this part, the below circuit needs to be considered.

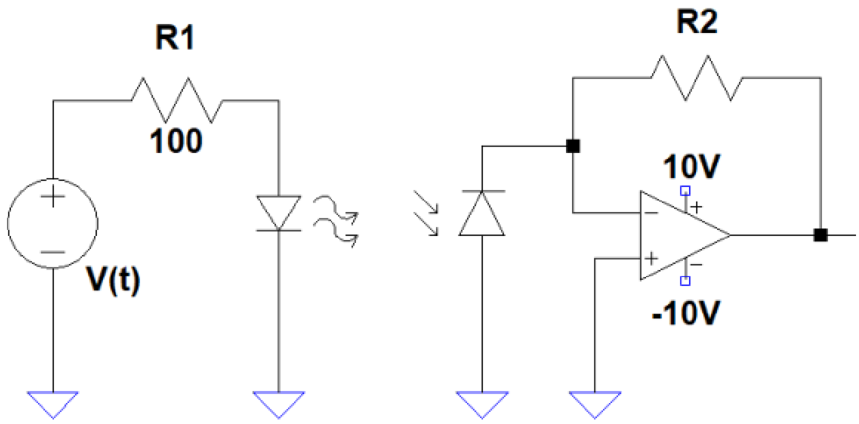

Figure 2: Circuit for part A

V(t) is a sinusoidal signal with 3V amplitude and 1 kHz frequency as mentioned before. The period is therefore 1 ms. While implementing the part with the LED, the LED needs to be connected in forward bias. To achieve that, I examined the SB-5010IRB datasheet and identified the leads. The p-side needs to be connected to the resistor and the n-side needs to be connected to the ground. That way, the LED is forward-biased. The function of R_1 in this circuit is to ensure that no high current passes that can damage the LED.

For the photodiode, since it needs to be connected in reverse bias, the p-side is grounded and the n-side is connected to the OPAMP. As seen from the datasheet [4], the induced current value is around 25-35 μA, however, the value can change since the LED and the photodiode are placed close such that most of the infrared radiations are detected. Whenever the LED is ON, it emits IR radiation and the photodiode induces a current. When the LED is OFF, no current is induced. This way, the current can be thought of as a negative rectified sinusoid. The current is negative since the photodiode operates in reverse bias.

This current is then converted to voltage by the OPAMP. The OPAMP in the circuit is an inverting amplifier model. Hence, considering the negative current, the OPAMP output voltage is expected to be a positive rectified sinusoidal signal. To find a value for R_2 so that the OPAMP is not saturated, we need to perform KCL at the (-) input of the OPAMP. Since the linear region is assumed and V_+ is grounded, KCL at the (-) input becomes:

$$V_- = V_+ = 0 \tag{1}$$

$$\frac{V_{out} - V_-}{R_2} = \frac{V_{out}}{R_2} = I_{ind} \quad \Rightarrow \quad V_{out} = I_{ind}R_2 \tag{2}$$

I_{ind} is the reverse-bias current of the photodiode. It is taken as positive since it is entering the (-) node, not leaving. Since for linear region V_{out}<10V should be satisfied, $I_{ind}R_2$ needs to be smaller than 10. Considering that typical I_{ind} ranges between 25 μA and 35 μA as seen in the datasheet [4]:

$$25\ \mu A < I_{ind} < 35\ \mu A \tag{3}$$

$$V_{out} = I_{ind}R_2 \leq 10\ V \tag{4}$$

$$R_2 \leq \frac{10\ V}{35\ \mu A} = 285.7k\Omega \tag{5}$$

Another condition is that the OPAMP's output voltage should be bigger than the turn-on voltage (V_{ON}) of the 1N4001 diode in the envelope detector, which is approximated as 0.7V in the datasheet [5]. This time, the minimum possible value of the OPAMP output voltage, therefore the minimum induced current, should be considered. Hence:

$$R_2 \geq \frac{V_{ON}}{I_{ind,min}} = \frac{0.7\ V}{25\ \mu A} = 28k\Omega \tag{6}$$

I first chose 56 kΩ for R_2, and then I constructed the first part of the circuit. The circuit is shown in Figure 3.

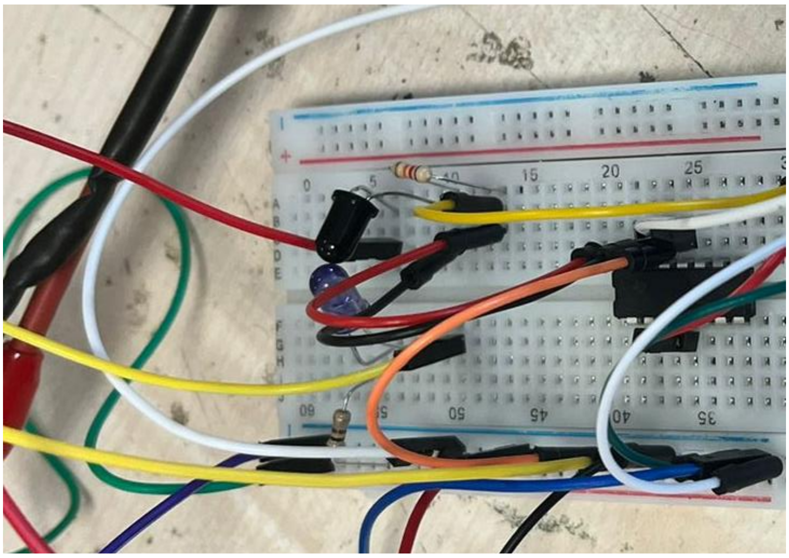

Figure 3: The first part implemented on the breadboard

The voltage on the LED is shown in Figure 4.

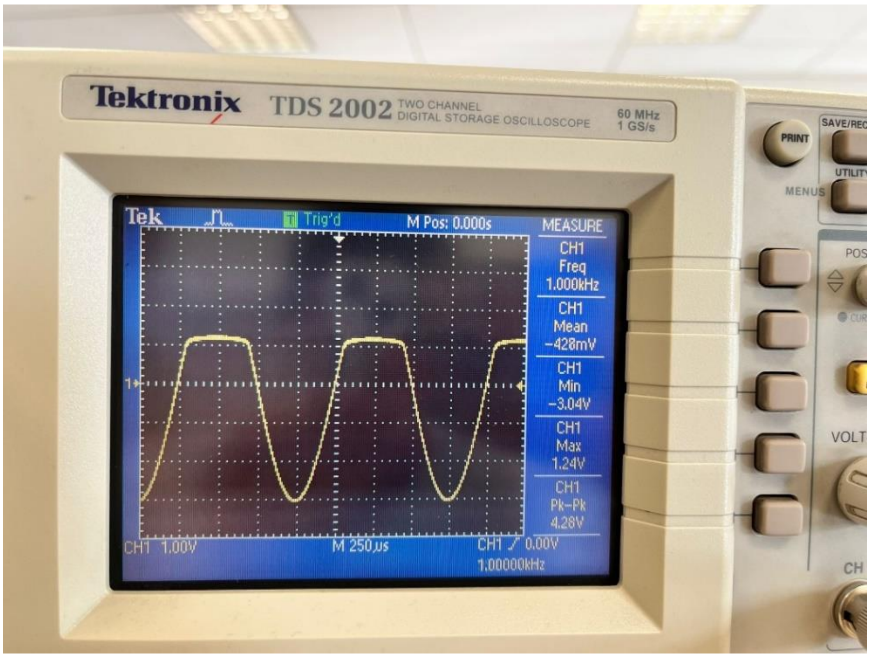

Figure 4: The LED's voltage

As seen in the figure, the voltage is clipped when it is higher than 1.24V. This corresponds to the ON state in which the LED emits infrared radiation. It keeps emitting until the peak voltage of 3V is reached and the voltage drops back to 1.24V. After the voltage across the LED falls under 1.24V, the emitting is stopped (OFF state) until the voltage reaches 1.24V again. The value of 1.24V corresponds to the forward voltage of the LED, which is given as 1.5V in the datasheet [2]. This difference might have occurred due to the measurement errors. Since the LED's maximum reverse voltage is 5V, the signal's minimum voltage -3V does not damage the LED.

The OPAMP's output is shown in Figure 5.

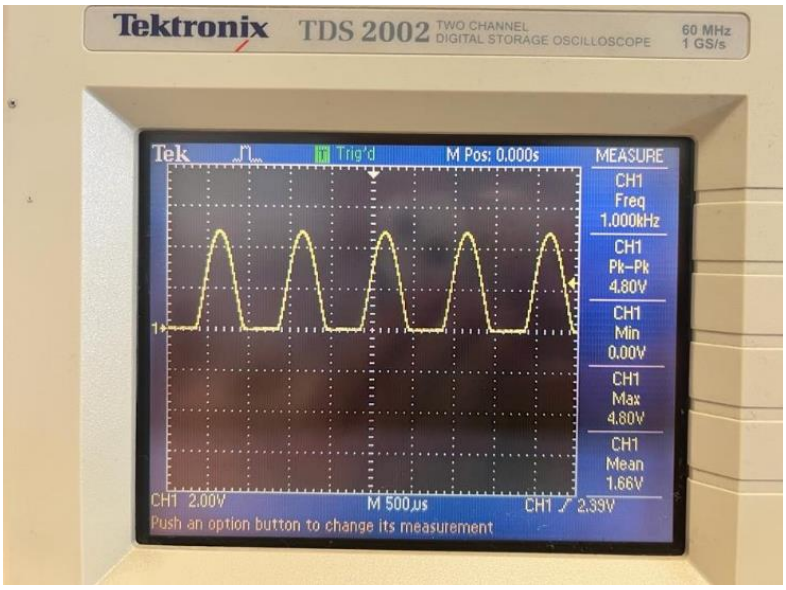

Figure 5: The OPAMP output with 56kΩ resistor

However, to maximize the voltage, I decided to increase the resistance. This time, I chose R_2 as 82kΩ since it is in the desired range. After setting up the circuit, the OPAMP's output is shown in Figure 6. The maximum voltage was 8.8V this time. As expected, the output is a rectified sinusoidal wave. This is because current is induced whenever the LED is in ON state, when it is OFF, there is no current. The photodiode working in reverse bias creates a negative current. When a negative current is induced, the OPAMP converts it into positive voltage since it is an inverting amplifier.

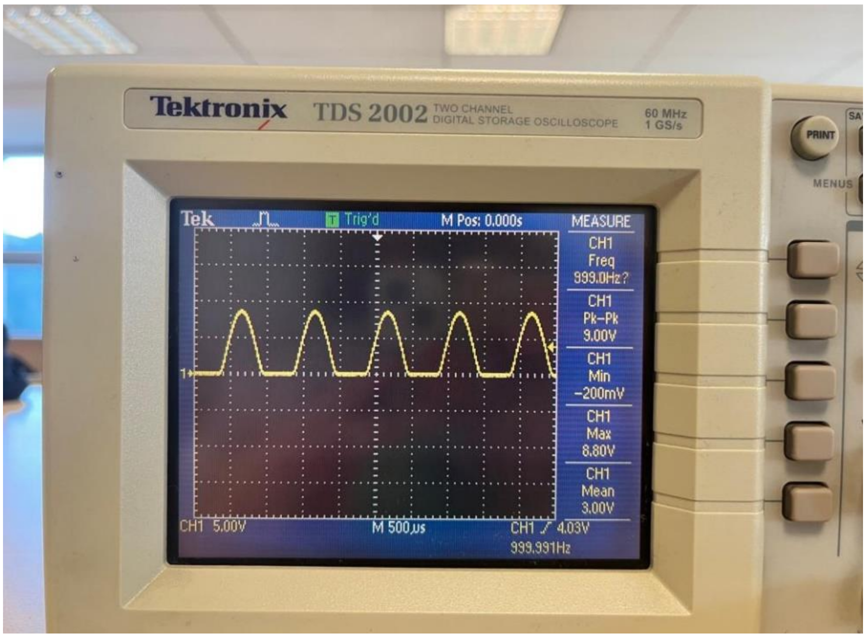

Figure 6: The OPAMP output with 82kΩ resistor

When R_2 is chosen greater than 285.7kΩ, for example 300kΩ, the output is saturated. For the 300kΩ case, the saturated output is shown in Figure 7.

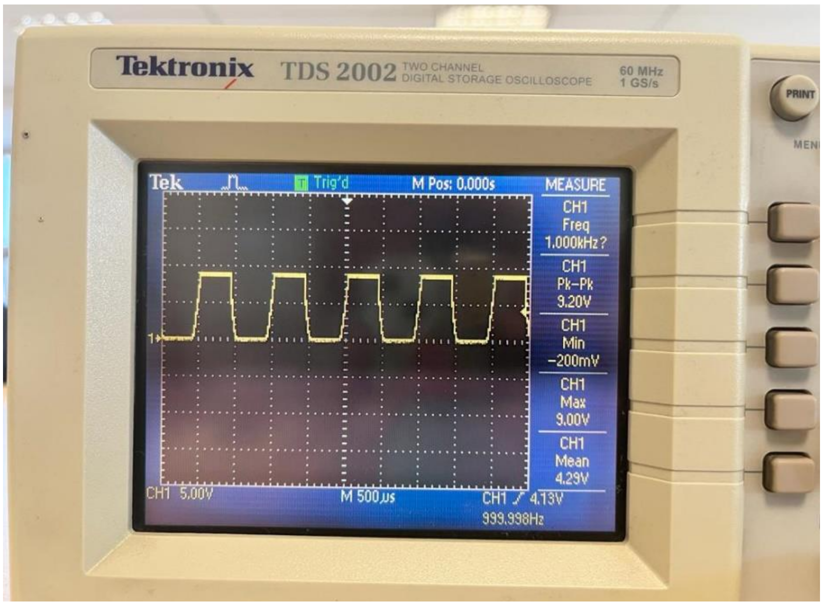

Figure 7: Saturated OPAMP output

Considering the peak voltage at the OPAMP's output, the induced current can be calculated as 8.8V/82 kΩ = 109μA. The reason why the current value is higher than expected is because the LED and the photodiode were placed with nearly no distance between them. Hence, the photodiode was able to detect all the IR radiation emitted by the LED. This also indicates the sensitivity of the photodiode and shows that the IR can be detected even with distance between the two components.

- **Part B – R_3 and C_1 selection**

The circuit to be implemented in this part is shown in Figure 8.

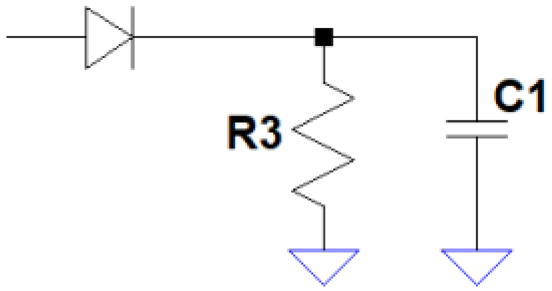

Figure 8: Circuit for part B

This envelope detector part of the circuit is actually a half-wave rectifier with a filter to convert a sinusoidal voltage to a DC voltage. This part contains a 1N4001 diode, a resistor R_3 and a capacitor C_1. For the 1N4001 diode, the turn-on voltage is approximately 0.7V [5]. When the voltage across the diode reaches this value, current can pass through it. This current also enables the capacitor to charge up. However, when the voltage across the diode becomes less than 0.65V, the current cannot pass anymore. This way, the capacitor can discharge only through R_3 [6]. The input voltage for this envelope detector is the OPAMP output from the previous part.

The output voltage of the rectifier $V_O(t)$ can be expressed as:

$$V_O(t) = \begin{cases} (V_p - V_{ON})e^{\frac{-t}{\tau}}, & \text{diode is OFF} \\ V_{in}(t) - V_{ON}, & \text{diode is ON} \end{cases} \quad (7)$$

where V_p is the peak value of the input voltage $V_{in}(t)$, τ is the time constant of the circuit, V_{ON} is the turn on voltage of the diode which is 0.65V.

This results in a ripple voltage at the output, as shown in Figure 9.

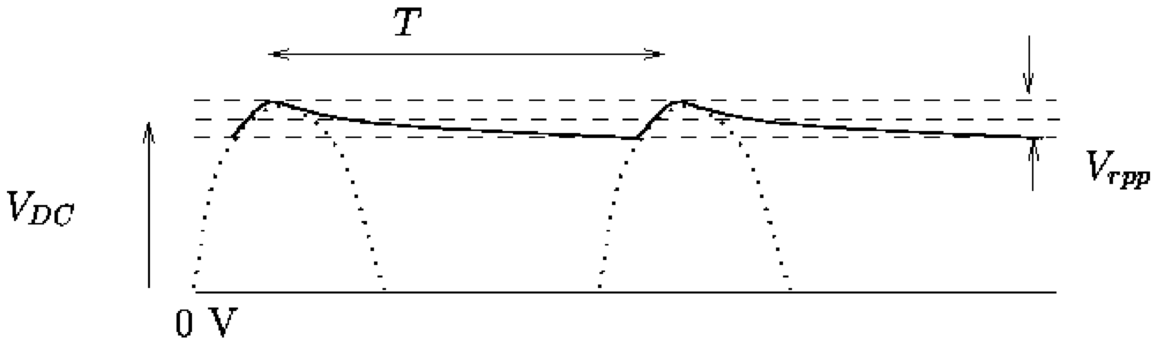

Figure 9: Ripple voltage [6]

To obtain DC voltage, the ripple should be as small as possible. Since the ripple is essentially the decaying voltage of the capacitor, in other words its discharging, the time it takes depends on the time constant (τ) of the circuit. In this case, the time constant is R_3C_1. When the time constant is much greater than the input voltage period, which is 1 ms for this experiment, the capacitor charges and discharges much slower compared to the input signal. This results in very small changes in the output voltage since there is not enough time for the capacitor to discharge. Thus, R_3 and C_1 should be selected as follows:

$$\tau = R_3C_1 \gg \; T_{input} \tag{8}$$

$$R_3C_1 \gg 1\,ms \tag{9}$$

To ensure a DC voltage, the R_3 and C_1 are selected as:

$$R_3 = 820k\Omega\,, C_1 = 10\mu F$$

$$\tau = R_3C_1 = 8.2s \gg \; 1ms$$

It should be noted that the values of R_3 and C_1 may be increased as much as possible to obtain even smaller ripples. With the selected values, the circuit is finalized and then implemented. Figure 10 displays the implemented circuit on the breadboard.

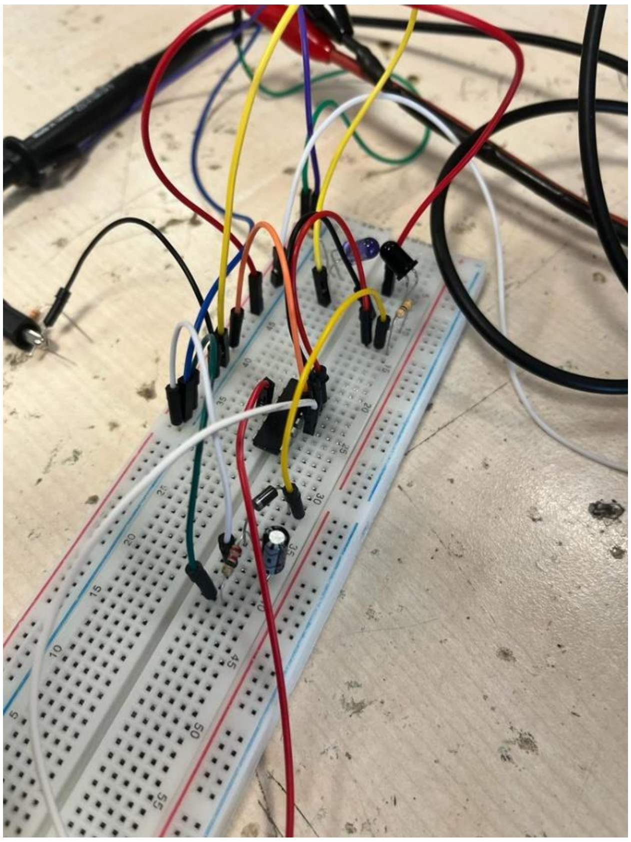

Figure 10: Circuit implemented on breadboard

The output is a DC voltage as expected. The output voltage is shown in Figure 11.

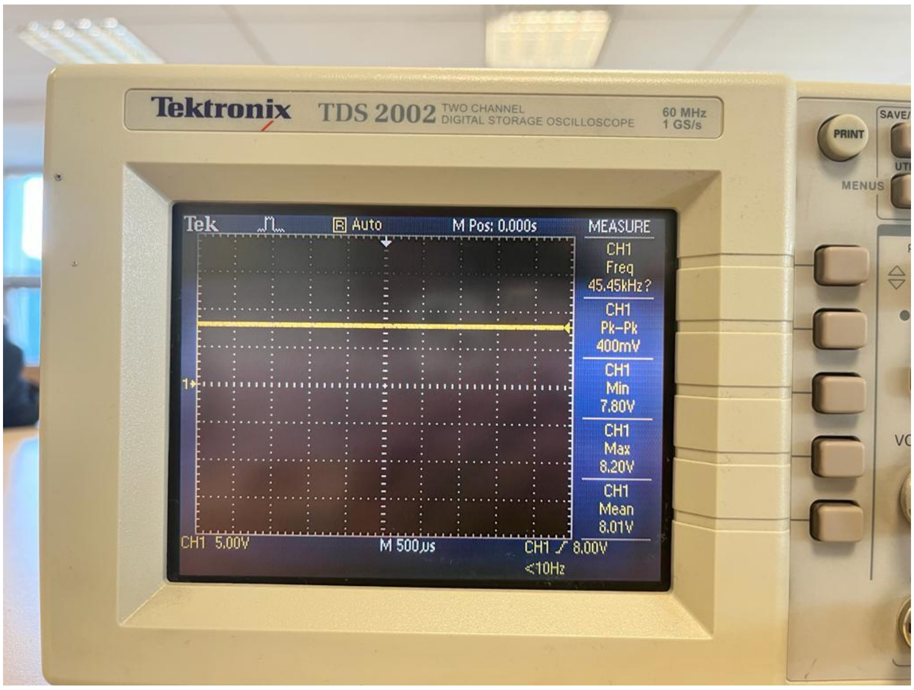

Figure 11: Output is a DC voltage

Considering the maximum values which is 8.2V for the output and 8.8V for the OPAMP sinusoidal output (and the rectifier's input), the diode's voltage can be found as 8.8-8.2=0.6V when it is ON. This complies to the forward voltage of the diode in the datasheet (0.7V) with minimal error, which might have occurred due to the measurement errors of the oscilloscope or the internal resistances of the components. The diode's forward voltage is also affected by factors like temperature and forward current, which are also indicated in the datasheet [5].

III. Conclusion

In this experiment, first I induced a current from a photodiode using the IR radiation of the LED. Then I converted this current first into an AC voltage using an OPAMP, then to a DC voltage using a rectifier. The results were successful, and I was able to observe a constant DC voltage at the output. I achieved this by first examining the datasheets of the LED and the photodiode, and also by understanding the working principles of these devices. The key to obtaining a successful result was also choosing the proper values for R_2, R_3 and C_1.

With this experiment, I also learnt some key points regarding these components. First, even though the induced current was indicated as in the 25-35 µA range, I calculated the induced current as 107.3 µA. The reason why it was higher than expected was that the LED and the photodiode was placed with no distance between them. This way, the photodiode detected nearly all the IR emitted by the LED. This shows that even when there was distance between them, the emitted IR would be detected with no big errors. While choosing R_2, I tried different values such that the OPAMP is not saturated but at the same time I wanted to obtain the voltage amplitude as large as possible. When I chose R_2 as 82k, I achieved this. To choose R_3 and C_1, their multiplication should be much bigger than 1 ms, the input voltage period. As the values for R_3 and C_1 are increased, the ripple voltage decreases and at the output a constant DC voltage is observed. I successfully obtained a DC voltage by choosing R_3=820kΩ and C_1=10µF.

In conclusion, this experiment was beneficial for me to learn the understand the voltage-current characteristics of photodiodes and LEDs, also the functions of OPAMPs and rectifier circuits. I also learned about converting an AC voltage into a DC voltage with this experiment. This knowledge will be helpful for me in my future experiments and projects.

References

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