ECE 342 Lab #1:
Transimpedance Amplifier Module for the Receiver

Bailee Bartash, Cameron Newland

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Abstract

The design, construction, and testing of a transimpedance amplifier (TZA) module for the receiver is described. As the third step in the design of an optical link, the investigation of different light-emitting diodes (LEDs) with a specific OP999 photodiode is shown. The design of the TZA is such that the circuit will produce a large gain and still be stable enough to avoid a phase shift in the feedback loop. The LED chosen to be used with the photodiode was the infrared LED. The component values were chosen such that a -3 dB attenuation occurs at 40 kHz. The TZA produced a -5.68 dB attenuation at a frequency of 40kHz, which is reasonable for this lab.

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1 Introduction

This report describes the design, simulation, and implementation of the TZA module. This lab will use the design of the TZA for a later, much larger project, the Optical Link Project. This project will take five different labs and combine them for one full project, shown in Figure 1.

Figure 1: An overview of the Optical Link Project [1]

This lab, however, focused only on the TZA design. The TZA consists of an op amp with a feedback resistor and a compensation capacitor in parallel to create a lowpass filter. A large feedback resistor ensures a large gain for the TZA while avoiding high frequencies that cause noise in the circuit (Figure 2). The maximized gain will become more important later in seeing how far apart the LED and photodiode can be separated and still allow for signal detection.

The frequency of the input source was 20kHz, and was used in both the simulation and the implementation stage. The measured output from the AC response has a cutoff frequency, or 3dB frequency, of 40kHz and transient response is a plot of the output, a sinusoidal signal with a frequency of 20kHz.

Section 2 of this report will overview the circuit design and analysis, Section 3 will discuss the simulation, and Section 4 will show the experimental implementation. Each section will detail everything that needed to be done in order to make the system work. The results of each stage are shown at the end of each section and in the discussion section (Section 5). The results for the simulation and implementation stages are analyzed and compared. Section 6 concludes the report. References are listed at the end.

2 Circuit Design and Analysis

This section analyzes the theory and calculations involved in designing the TZA module for the receiver with given design specifications and available component values. Choosing the LED that best worked with the photodiode and determining the component values for the TZA are discussed below. The design of the TZA and module are shown in Figure 2.

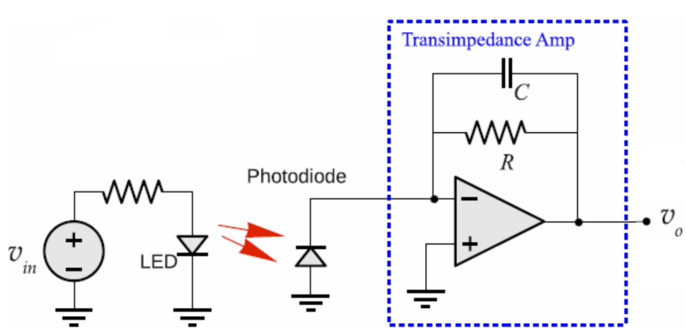

Figure 2: A diagram showing the final schematic of the TZA including the photodiode and the LED [2]

2.1 Choosing the LED for signal transmission

LEDs are specific in that light is only emitted at a certain wavelength range, hence the different colors. The LEDs available for Lab 1 were infrared (940 nm peak wavelength), red (625 nm), blue (470 nm), and green (560 nm).

The LED to be implemented with the TZA is the LED that will be best detected by the OP999 photodiode. The photodiode has a peak relative response over certain wavelengths while each LED has a peak relative radiant intensity at a certain wavelength. Choosing an LED for optimal signal transmission is simply a matter of comparing the relative response vs. wavelength plot of the photodiode to the relative radiant intensity vs. wavelength plots of each of the diodes.

By comparing the peak frequencies at which the photodiode and LEDs operate, the infrared LED was used as it's peak relative radiant intensity is at 940 nm and matches up the closest to the OP999 photodiode's peak relative response wavelength which is about 900 nm, see Figures 3 and 4.

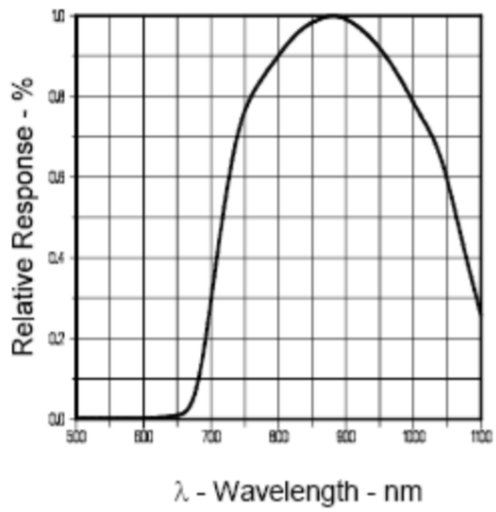

Figure 3: OP999 photodiode relative response vs. wavelength plot [3]

The best response of the photodiode ranged between 800-950nm wavelengths.

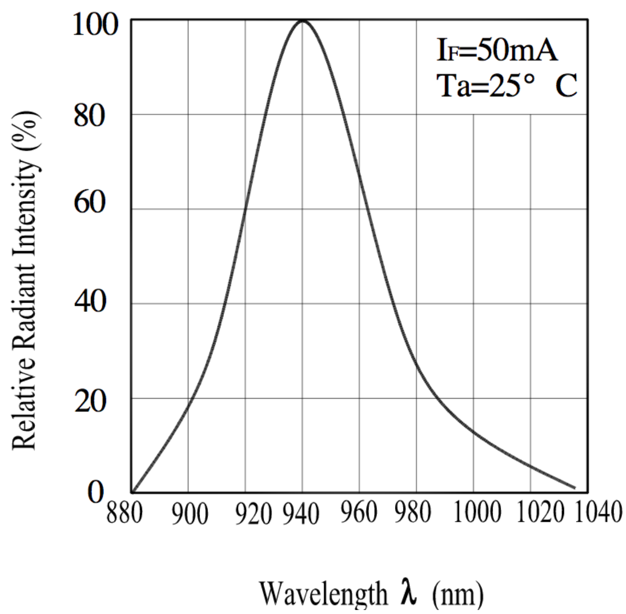

Figure 4: IR1503 infrared LED relative radiant intensity vs. wavelength plot [4]

The other three available LEDs (red, green, and blue), were not optimal for use with the photodiode as their peak relative radiant intensity wavelengths were much lower than that of the photodiode, see Figures 5, 6, and 7 below.

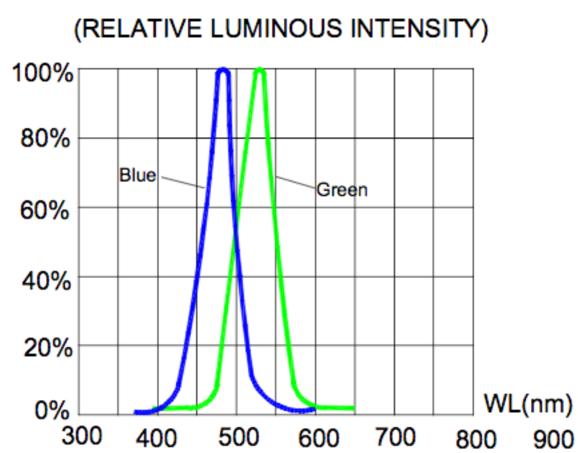

Figure 5: C503B blue LED relative radiant intensity vs. wavelength plot [5]

The blue LED in the Figure 5 is the LED that was proposed for the lab. The blue LED has a peak relative luminous intensity at a wavelength of 475nm. The green LED in Figure 5 is not the same green LED proposed for the lab.

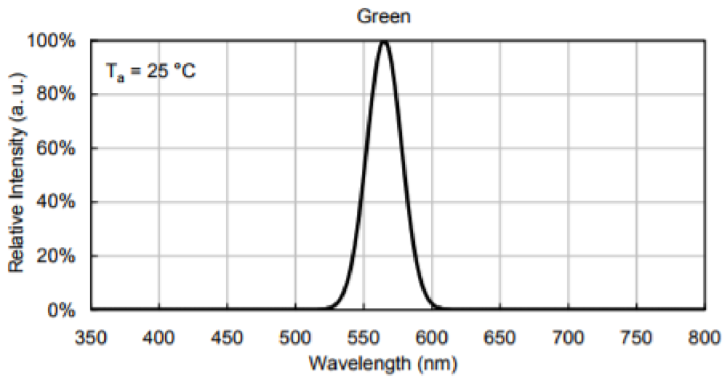

Figure 6: WP7113SGC green LED relative radiant intensity vs. wavelength plot [6]

The peak luminous intensity of the green LED with a wavelength close to 560nm.

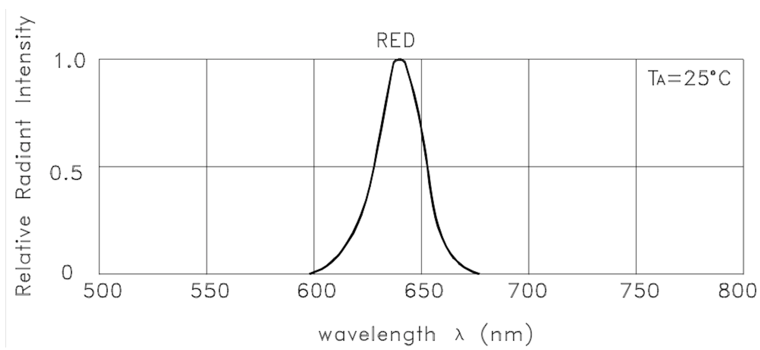

Figure 7: WP7113SEC/J3 red LED relative radiant intensity vs. wavelength plot [7]

The red LED has the best luminous intensity with a wavelength close to 640nm.

2.2 Transimpedance Amplifier Design

As shown in Figure 2, the TZA consists of an op amp, a feedback resistor R_f, and a capacitor C_f. In simulation, the photodiode is represented by a current source in parallel with a capacitor C_in. The final simulated circuit is shown in Figure 8.

This lab implemented an LF347 op amp for simulation and an LF356 op amp for the experiment. While both op amps behave the same way, the LF347 op amp was used in simulation at the suggestion of the instructor, and the LF356 op amp was used in implementation due to ease of use (LF347 has four op amps on its chip, LF356 has only one).

C_in represents the total capacitance of the photodiode. According to the OP999 photodiode data sheet, this capacitance is 4 pF, so that is the value of the capacitor in the simulation.

In order for the TZA to avoid a 180° phase shift in the feedback loop, the pole frequency, or the 3dB frequency, was set to 20 kHz. This was given by design specifications in the lab handout to ensure stability. The rail voltages for the op amp were set to ±12 V, as those are the voltages available from the power brick for implementation.

The TZA allows a large signal gain, large output voltage, and large frequency bandwidth all at once, with the trade off being possible instability in the TZA. The compensation capacitor, C_f, in parallel with a feedback resistor, R_f, creates a lowpass filter for the amplifier to remedy this. The values of R and C were chosen so to achieve high gain and to ensure the cut off frequency was small enough to avoid the phase shift discussed above.

This TZA will be first amplifier in the receiver of the optical link and will set the noise floor for the receiver. As such, the gain should be as large as possible for the best noise performance. The feedback resistor sets the gain, and as above, C_f limits the frequency response to twice the cutoff frequency, $2f_o$, so the amplifier remains stable. The smallest capacitor available is 10 pF, but due to the parasitics of the solderless bread board to be used in implementation that range from 1-10 pF, the chosen value for C_f was 22 pF.

The equation for the output voltage is simply Ohm's law, current multiplied by resistance. The current for the entire amplifier is the input current and the resistance is simply the value of the feedback resistor (Equation 1).

$$v_o = i_s R_f sin(2\pi ft) \tag{1}$$

The gain for a non-inverting op amp (which describes the LF347 and LF356) is the ratio of the output voltage over the input, and is also the value of the feedback resistor (Equation 2).

$$Gain = \frac{v_o}{v_{in}} = R_f \tag{2}$$

The cut off frequency, which is the same as the 3dB frequency, can be calculated by taking the inverse of 2π times the value of the feedback resistor times the value of the compensation capacitor (Equation 3).

$$f_{cutoff} = f_{3dB} = \frac{1}{2\pi R_f C_f} \tag{3}$$

As given in the lab handout, the cut off frequency must be 20 kHz to ensure stability. This means that the 3dB frequency must be greater than or equal to twice the cut off frequency (Equation 4).

$$f_{3dB} \geq 2f_o = 40kHz \tag{4}$$

Since C_f was already determined as 22 pF and f_{dB} was 40 kHz, the value of R_f can easily be calculated using Equation 5.

$$R_f = \frac{1}{2\pi f_{dB} C_f} \tag{5}$$

Here, the value for R_f was determined to be 181 kΩ.

As specified by the lab handout, the input current signal was sinusoidal, so within NGspice the DC current, I_{dc}, was set to 0 A and the AC current, I_{ac}, was set to 1 A. The peak current, I_p was determined by taking the ratio of the peak voltage, which was the positive rail voltage V_{cc}, to the feedback resistor (Equation 6).

$$I_p = \frac{V_{cc}}{R_f} \tag{6}$$

In the above equation, V_{cc} is +12 V and the value of the feedback resistor is 181 kΩ, so the value of the peak current should be set to about 66 μA. To ensure that this current would not be too high, the current used in simulation was scaled back to 50 μA.

3 Simulated Performance

Using Sue2, a schematic was created for the TZA and run using NGspice. A current source and a capacitor were used in place of the photodiode as described above. See Figure 8 for the final simulated circuit.

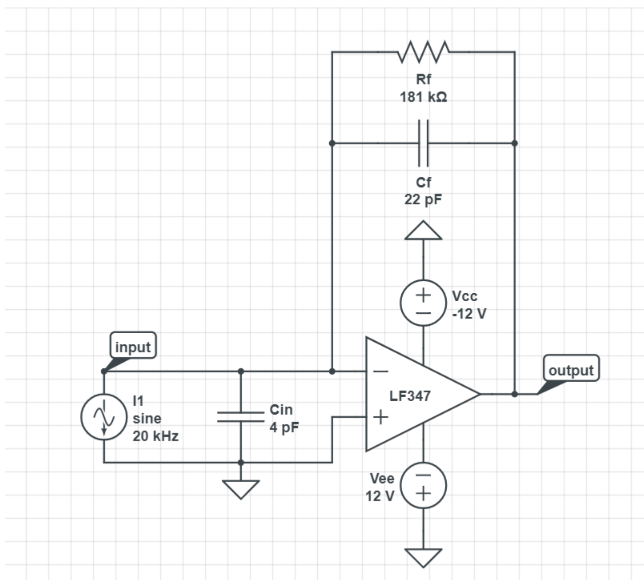

Figure 8: Final Sue2 schematic implemented during simulation

Using MATLAB, two plots were generated, one of the frequency response (AC Analysis), and the other of the simulated output (Transient Response), see Figure 9.

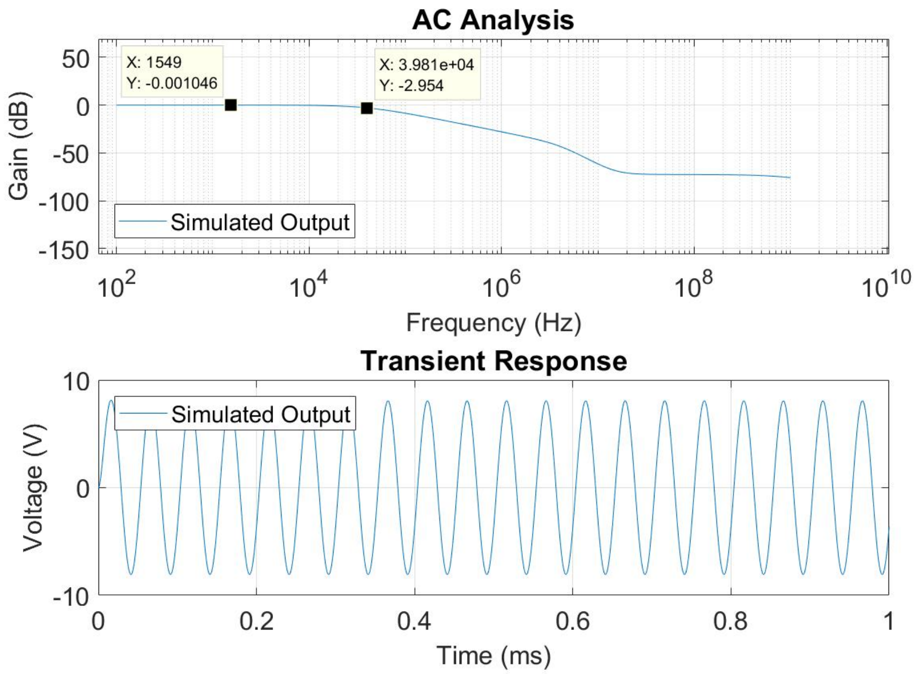

Figure 9: MATLAB plot of simulated AC Analysis and Transient Response

To determine the gain at the 3dB frequency, two plot points were taken using the MATLAB cursor function, one before the change in gain (anywhere on the plot below 40 kHz) and one exactly at 40 kHz. In doing this, the difference found was -2.954 dB attenuation, which is very close to the ideal -3 dB. Plotting the transient response was to ensure the correct output (a sinusoidal wave) was the result of the simulation.

4 Experimental Implementation

The final schematic of implemented TZA is given in Figure 10.

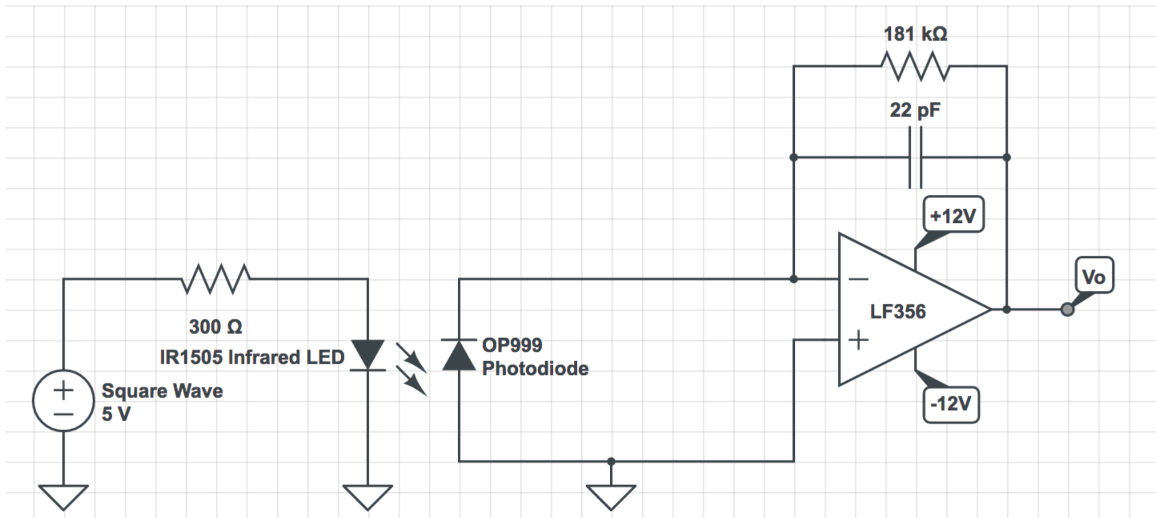

Figure 10: A final schematic for the Lab 1 TZA design

Sue2 was unable to simulate with a photodiode, so a current source in parallel with a capacitor represented the photodiode as discussed above. Implementing an LED with with photodiode in the design required a resistor R to be added in series with the infrared LED to prevent the LED from drawing too much current, shown in Figure 10 above.

The maximum LED current was 10mA. The maximum LED voltage was 1.5V, as described in the data sheet. A 5V power source with a source resistance of 50Ω was used to light up the LED. The resistor R was calculated taking all of these factors into consideration, see Figure 11 below.

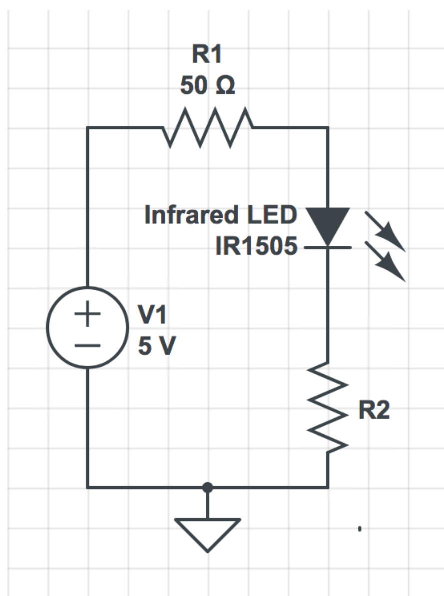

Figure 11: A schematic showing the 5V square wave source, infrared LED, and the desired resistor R.

Solving for the current of the source could be found with the following equation.

$$i = \frac{V1 - V_d}{R1 + R2} \tag{7}$$

V_d is the max voltage that can be supplied through the LED, or 1.5V, V1 is 5V, and R1 is 50Ω. Given that the max current through the LED was 10mA, solving for the resistance R gave 300Ω.

Figure 10 shows the final schematic including the values found in the simulation section as well as the LED and the voltage source supplied to the LED.

The square wave input shown in Figure 11 has a peak to peak voltage of 5V with an offset of 2.5V so that the square wave goes from 0-5V. The source was chosen because the maximum reverse-bias voltage of the LED was 5V. The frequency of the input was set to 20kHz. To get this input, Waveforms was used and the supply voltage was set to these standards. The Digilent was used to power a 12V power brick, which was in turn used to power the LF356. The Sue2 simulation used an LF347 op amp, but was unnecessary because it contained 4 op amps with eight pins, so an LF356 op amp was used. The two op amps simulate the same, so redoing the simulations was not necessary.

The waveform output was measured on channel 1 to make sure the right input was sent to the LED. On channel 2, the output of the TZA was measured. By using a networks functions in Waveforms, it was possible to graph a frequency response of the TZA. Then, exporting the data as a .csv file to MATLAB made it possible to plot the measured and simulated AC and transient responses of the TZA to compare their outputs.

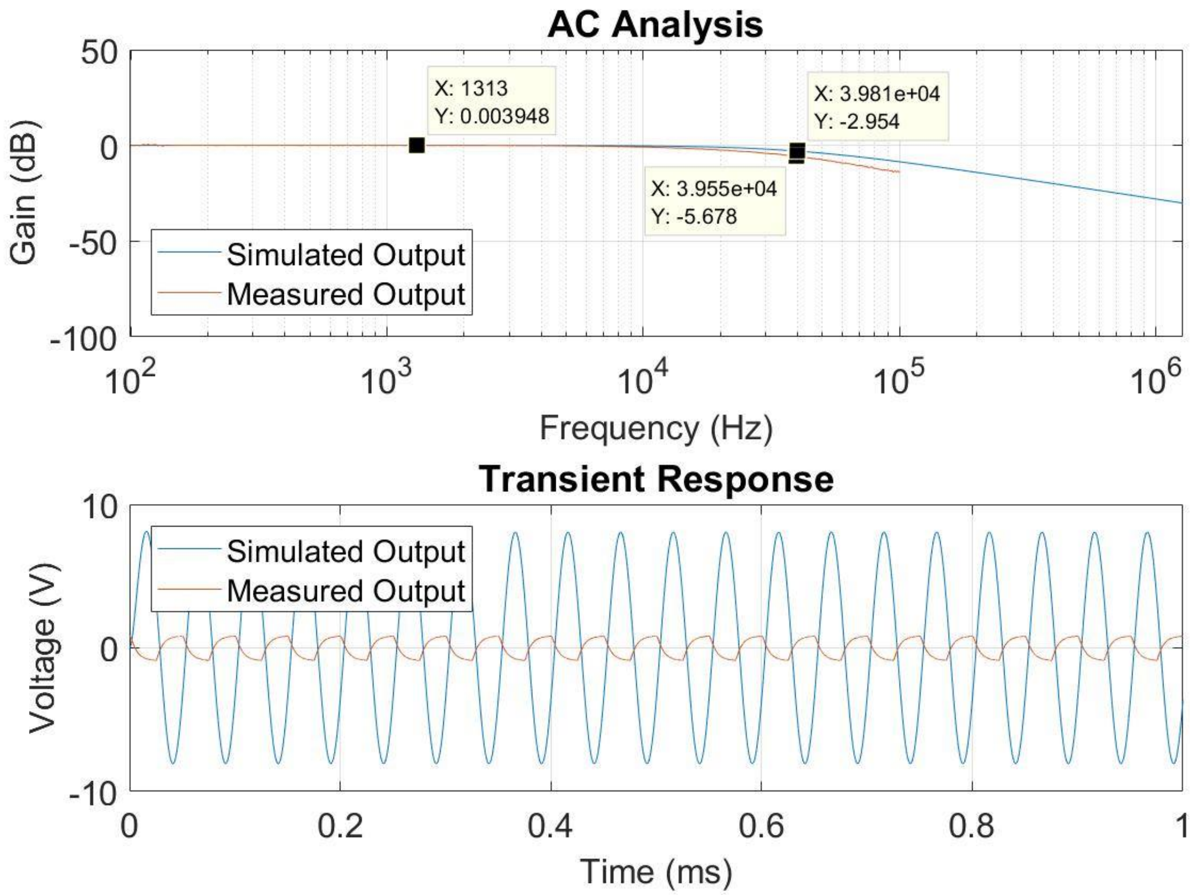

Figure 12: The measured and simulated AC and transient responses of the TZA

The frequency response was measured between 10-100kHz using the networks function mentioned earlier. Frequencies larger than 100kHz cause issues with the networks function. The measured response got close to one decade above and below the cutoff frequency. The cutoff frequency was measured in the simulation to be 40kHz, or the -3dB frequency. The easiest way to check this was to use the cursors to see the difference between a gain much less that 40kHz and compare it to around 40kHz to see if the gain has an attenuation of -3dB. At 40kHz, the simulation gave a -3dB gain and the measured gain was -5.678dB, which was close enough.

By examining was the transient output, the measured output was shown to have a frequency the same as the simulation, 20kHz. Also, the simulated response clearly represented a sinusoidal signal. The measured response did not represent a sinusoidal signal as much as the simulation, however. The measured gain closely represented a capacitor charging and discharging signal, as the rising edge appeared to be an increasing, decaying exponential and the other a decreasing, decaying exponential function. This is one possible source of error that occurred in the lab.

The magnitude difference between the simulated and measured responses was not concerning because the peak value of the current source that was supposed to represent the photodiode was manually set to avoid saturation. But, the current from the photodiode was so small that the 181k gain would not come close to saturating, as shown in Figure 12.

5 Discussion

The circuit operated as expected. The subtle differences between each likely came from imperfections in the components and not from the design. Table 1 below outlines the attenuation at 40 kHz for the design, simulation, and experimentation.

Table 1: Transimpedance Amplifier Summary

	Design	Simulated	Measured
Attenuation @ 40kHz	-3dB	-2.95dB	-5.68dB

The accuracy of the MATLAB cursors tool is limited as it can only get close to the 40kHz. As stated earlier, the -5.678dB attenuation was close enough to be considered reasonable.

The hardest part of this lab was figuring out how to operate Waveforms and the Digilent to get the output expected on channel 2.

At first, the TZA output could not be seen on channel 2. The supplied power to the LED should have worked, but the infrared LED was switched with the blue LED to make sure that the LED was being powered. The reason for this is that the infrared emits light at a wavelength outside the visible light spectrum.

After implementing the correct time scale needed to be used in order to see the output at 20kHz, the output became better before changing the LED back to the infrared. After doing that, the expected sinusoidal-like output was not as clear.

The output looked like two decaying exponential functions, the first increasing and decaying and the other decreasing and decaying. After inspecting, the reason for this seemed to focus on the 22pF capacitor, as its voltage cannot jump. For this reason, the output would never be a perfect sinusoidal signal.

As mentioned before, the final part of the lab, once building the circuit, was to take the measured output from Waveforms and save the data as a .csv file. Once doing this, the data could then be uploaded to MATLAB to plot both the simulated and measured results on the same graph. The benefit from this was that both the simulated and measured results could be examined on the same MATLAB plots which is not only easier for each student, but for the reader as well. Before this recent semester, comparing measured with simulated results came from taking pictures of the oscilloscopes used in lab and then comparing it to the simulated results on MATLAB. Now it is much more accurate and visually appealing.

6 Conclusion

In this lab a transimpedance amplifier module for the receiver of an optical link was designed. An infrared LED, in series with a 300Ω resistor, was powered by a 5 V voltage source, whose signal was then detected by the photodiode, which delivers a current signal input that can be read as an output voltage by the TZA. In simulation, Sue2 and NGspice were used to create and run schematics, and MATLAB was used to plot the data. During implementation, a Digilent was used as both a function generator and an oscilloscope, and the data was then taken from the Digilent and plotted on top of the MATLAB plot with the simulated results, with some minor changes in the plot function to account for differences in amplitude between the signals. The end goal was to observe the attenuation at the cut off frequency. In an ideal case, this would have been -3 dB, though in experimentation, this was actually -5.678 dB. This attenuation is close enough, in that the TZA still functions as desired, turning the current signal of the LED into a voltage output.

References

[1] David Kotecki. ECE 342 Fall 2017 Optical Link Project. Page 1. The University of Maine, 2017.

[2] David Kotecki. ECE 342 Fall 2016 Optoelectronic Link Project Lab 1: Transimpedance Amplifier Module for the Receiver: LEDs, Photodiodes and Transimpedance Amplifiers. Page 1. The University of Maine, 2017.

[3] David Kotecki. ECE 342 Fall 2017 Datasheets: OP999 PIN Silicon Photodiode. Page 5. The University of Maine, 2017.

[4] David Kotecki. ECE 342 Fall 2017 Datasheets: IR1503 Infrared LED. Page 4. The University of Maine, 2017.

[5] David Kotecki. ECE 342 Fall 2017 Datasheets: C503B Blue LED. Page 7. The University of Maine, 2017.

[6] David Kotecki. ECE 342 Fall 2017 Datasheets: WP7113SGC Green LED. Page 3. The University of Maine, 2017.

[7] David Kotecki. ECE 342 Fall 2017 Datasheets: WP7113SEC/J3 Red LED. Page 3. The University of Maine, 2017.