Optical Uplink

Transimpedence Amplifier Module

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Abstract

The design, simulation, and construction of a transimpendence amplifier are described. An LF356 operational amplifier, with rail voltages of ±12V was used to convert the current output supplied by an OP999 photo-diode to a measurable voltage. An infrared LED was driven with a 20kHz, 5V square wave in order to generate the input for the photodiode. An output voltage of 8V$_{pp}$ was generated. The Amplifier operated with a 3dB cuttoff frequency of 41kHz.

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1 Introduction

This report describes the design, implementation and test of a transimpedance amplifier(TZA). The TZA consists of an inverting operational amplifier and a feedback resistor. The TZA takes an input current and converts it to an output voltage. The TZA allows for a very high gain. The circuit uses a photodiode to generate an input current. A compensation capacitor was used in order to ensure that the TZA remained stable. Figure 1 belows demonstrates where in the optical link relay design the TZA falls.

Figure 1: Block diagram for optical uplink[1]

Section 2 of this report describes the design of the TZA as well as the rationale behind LED choice. Simulations are discussed in section 3 and experimental results are in section 4. A discussion of the results, sources of error, and areas of possible improvement are outlined in section 5. Section 6 concludes this report.

2 Circuit development

This section covers the design choices associated with the TZA and LED module. In order to choose an appropriate LED the LED datasheets were used. The operational amplifier was provided for the lab as was compensation capacitor[1]. Figure 2 is the schematic of the TZA as well as the LED.

The LED circuit in Figure 2 will not be included in the optical uplink design. The LED circuit in this lab was designed for testing purposes only. The resistor is chosen to be a sufficient value as to not exceed the breakdown current of the diode.

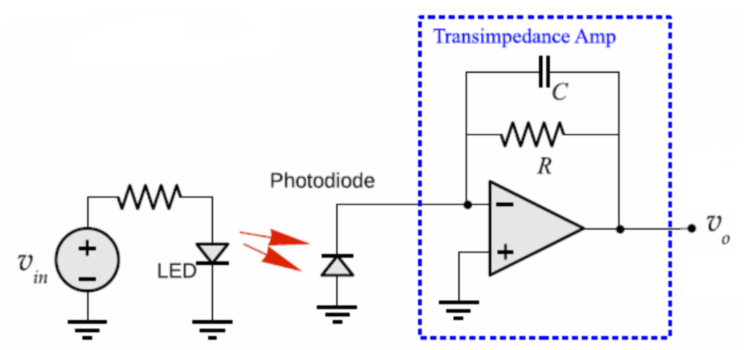


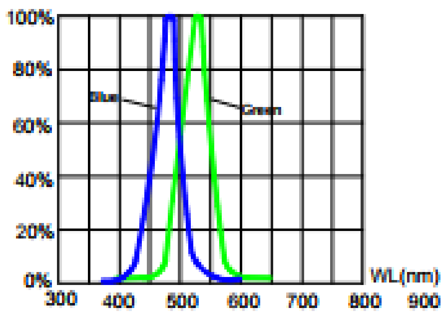
Figure 2: Basic Circuit Schematic for Design[2]

Section 2.1 describes how the LED was chosen. Section 2.2 describes the design of the TZA.

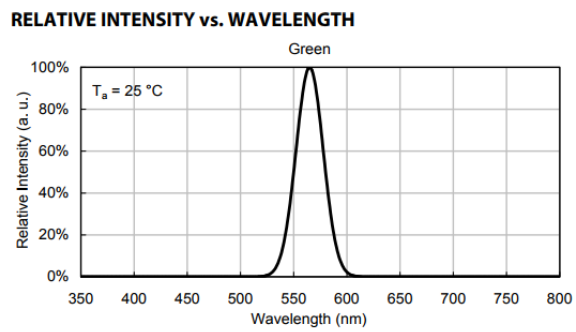
2.1 Choosing an LED

The LED is an integral part of the circuit design. In order for current to be emitted from the reverse-biased photodiode a incident light source is required. The photodiode used in this lab is a reverse-biased PIN silicon photodiode, the OP999. When an incident light of the proper wavelength and strength is used to activate the OP999, there is a transfer of energy from the photons from the light to the atoms inside the OP999.

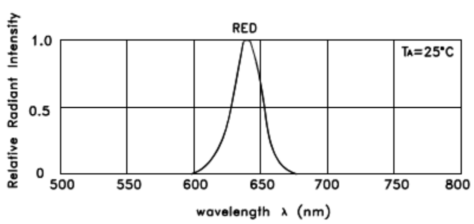
The electrons freed during this reaction will induce a reverse current from the OP999. There is also another current that is present at all times called dark current. This is a leaking current produced by photodiodes from the natural light. The current is small, but causes undesired affects on the circuit in the form of noise. Since the OP999 photodiode is reverse-biased, the dark current is increased. However, the noise for the purpose of this lab created by the dark current is negligible.



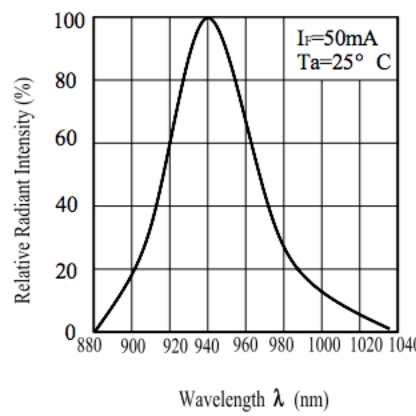
(a) Blue LED intensity v. wavelength [3]



(b) Green LED intensity v. wavelength [4]



(c) Red LED intensity v. wavelength [6]



(d) Infrared LED intensity v. wavelength [7]

Figure 3: Intensity graphs for LED's

The OP999 photodiode requires that for a maximum current output, a wavelength of 935nm needs to be emitted from the light source[5]. The light source will be chosen from among four light emitting diodes(LED) seen in Figure 3. Figure 4 below gives the spectral response of the OP999 photodiode.

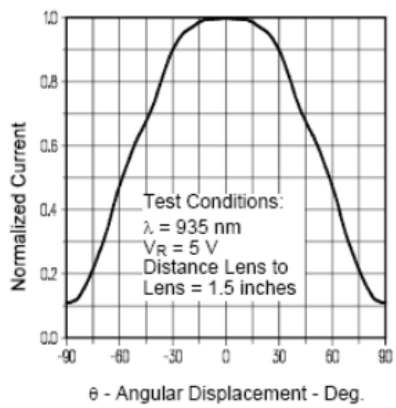


Figure 4: Spectral response of OP999[5]

The blue, bright green and red LED's ranged from 465nm to 640nm. These outputs would not have worked as a wavelength of 700nm will achieve only 20% of the photodiode's max current output. The Infrared LED, IR1503, has a wavelength of 940nm, which incidentally is what is required for the photodiode to achieve 95% or more of it's max current output. Table 1 below shows the values for maximum intensity for each LED.

Table 1: Maximum intensity wavelengths

Type of LED	Blue LED C503B-BCS/BCN-030	Green LED WP7113SGC	Red LED WP7113SEC/J3	Infrared LED OP999
Max Intensity Wavelength (nm)	465	565	625	940

2.2 Design of transimpedance amplifier

The schematic of the TZA is shown in Figure 5. The choice of TZA is that it provides large gain while still maintaining a large frequency bandwidth.

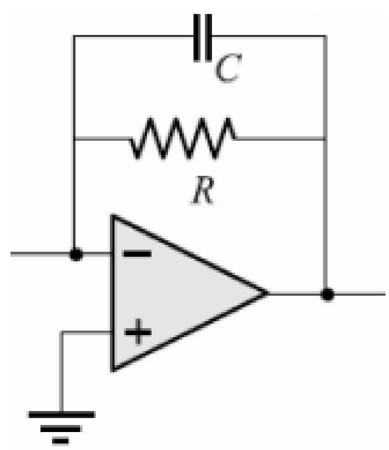


Figure 5: Transimpedence amplifier [2]

The frequency limit of the TZA is described by Equation 1.

$$f_{limit} = \sqrt{\frac{GBW}{2\pi RC_{pd}}} \tag{1}$$

GBW is the gain product, R is the feedback resistance and C_{pd} is the parasitic capacitance of the photodiode. The closed loop gain of the TZA is described by Equation 2.

$$Gain = \frac{v_0}{i_i} \tag{2}$$

Where v_0 is the output voltage and i_i is the input current. By performing Kirchoff's Current Law(KCL) at the noninverting input of the op-amp, the gain can be found to be Equation 3.

$$Gain = R_f \tag{3}$$

R_f is the feedback resistance of the TZA. The gain of the TZA can be made as large as the feedback resistance. This, however, will likely lead to the amplifier becoming unstable. Therefore, a compensation capacitor should be used to ensure stability. The 3dB cutoff, as provided by the lab manual states that $f_{3dB} \geq 2f_0$. From this, the 3dB cutoff can be found via Equation 4

$$f_{3dB} = \frac{1}{2\pi R_f C} \tag{4}$$

Using the 22pF provided by the briefing[1], a feedback resistance of 180kΩ can be found. Using these components a cut off frequency of 39.8kHz is acheived.

3 Simulations

This section describes the simulation of the TZA using NGSpice intregrated with Matlab.The output voltage and frequency response were simulated using these two prgrams. The OP999 photodiode was simulated by converting it to an equivalent circuit, seen in Figure 6.

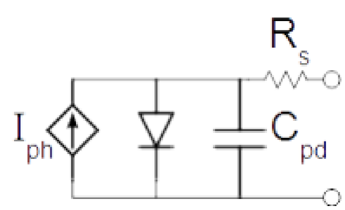


Figure 6: Equivalent ciruit of photodiode[2]

The final circuit that was simulated is shown in Figure 7.

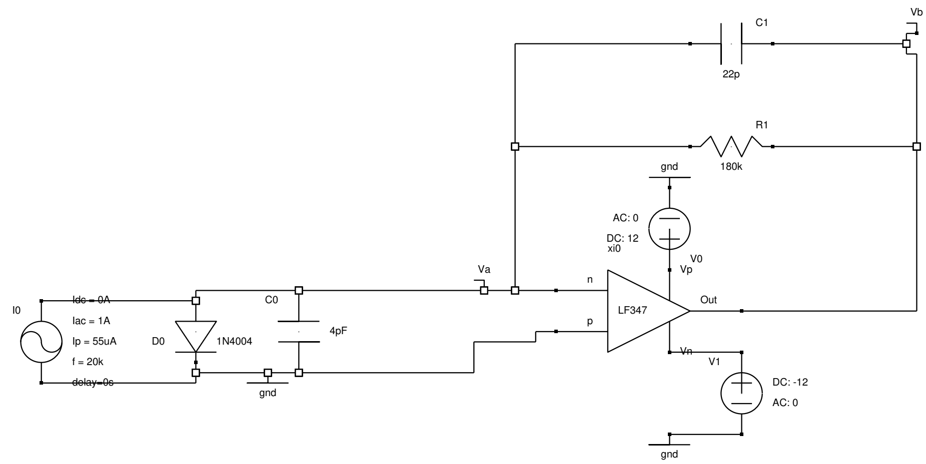


Figure 7: Equivalent ciruit of photodiode[2]

First the output voltage was simulated, and then finally the frequency response.

3.1 Output voltage

The output voltage was simulated using a transient analysis in NGSpice. Figure 8 below shows the unsaturated output voltage of the TZA. If the TZA were to operate while saturated it would produce distortion and the output would no longer behave linearly.

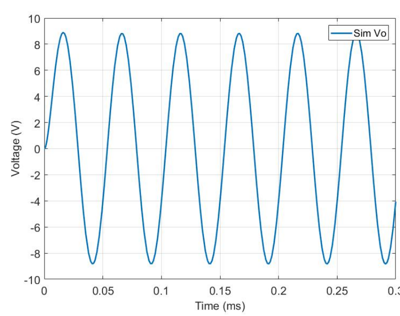


Figure 8: Simulated transient analysis of TZA output voltage

Notably, this is the op amp operating at the maximum input current prior to saturation. This provides the highest operating condition at which the circuit still behaves linearly. The other circuit parameter of interest was the frequency response.

3.2 TZA frequency response

The TZA gain was measured doing an AC analysis in NGSpice. The 3dB cutoff should be greater than 40kHz. The pole frequency should be greater than 40kHz in order to ensure that TZA remains stable and does not turn into a oscillator.The simulated frequency response is found below in Figure 9.

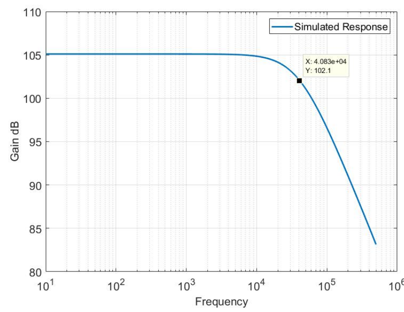


Figure 9: Simulated AC analysis of TZA Gain

The 3dB bend was found to be at a little greater than 40kHz. This ensures that the op amp remains stable under operating conditions.

4 Experimental implementation

The experimental design required only one change. The LF347 op amp was switched to an LF356 op amp. The LF347 operated with much higher noise than the LF356. Further information is found in the Discussion section. The following results were found using the simulated values and with the distance from LED to diode being several centimeters apart. The final circuit is shown in Figure 10 below.

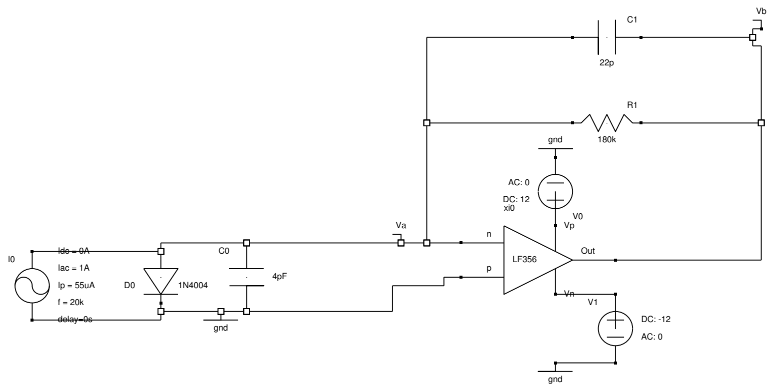


Figure 10: Experimental circuit schematic

First the output voltage was measured and then finally the frequency response was measured.

4.1 Output Voltage

The measured voltage output is found below in Figure 11.

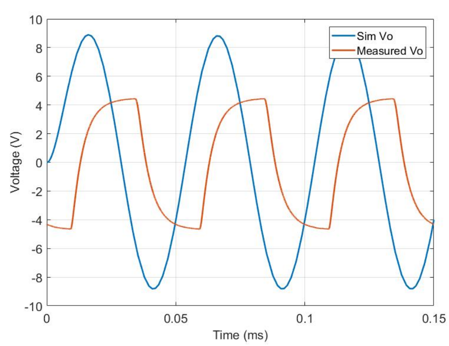


Figure 11: Voltage output of TZA: sim and experimental

The output signal was well within range and did not saturate the op amp. A notable discrepency is that the measured signal is not a perfect sinusoid. Finally, the frequency response was measured.

4.2 Frequency Response

The measured frequency response is found below in Figure 12. The actual gain of the circuit could not be measured, but a frequency sweep could be done using the Digilent Discovery 2's network analyzer.

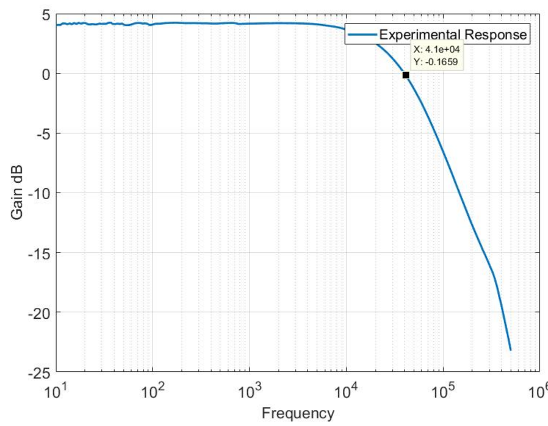


Figure 12: Experimental AC Analysis: Gain v. Frequency

The 3dB frequency was greater than the required 40kHz. Notably, the network analyzer could only generate data reliably upto 500kHz, unlike simulations which were performed up to 10MHz.

5 Discussion

Based on the development and design of the transimpedance amplifier, the actual results were similar, but with some variations. The voltage output of the simulated transimpedance amplifier was approximately 18V_{pp}. The measured value of the voltage output of the practical amplifier fell well short of that at approximately 8V_{pp} This is due to the current being provided by the current source in the simulation was the max allowable current before saturation and the photodiode's output current is well below that limit. The other noticeable difference is the shape of the outputs when compared. The simulated output is a smooth sinusoid which doesn't display the normal behavior of capacitors. The experimental output has discontinuities due to the exponential charging of the capacitor in the feedback of the TZA.

It also must be assumed that real-world factors had a parasitic effect on the circuit as well. The photodiode must be positioned properly with the LED, and even then, there will be some loss unless more of the photons are redirected towards the photodiode.

Finally, an LF356 op amp was chosen over the LF347 because the LF356 produced an output signal with far less noise. The LF356 benefits from having fewer onboard op amps, reducing interference at the output.

6 Conclusion

The design, simulation, and implementation of the transimpendence amplifier have been explained. Lab specification required that the TZA have an 3dB cutoff frequency of at least 40kHz. The TZA takes a very small input current and then outputs a measurable voltage signal. The TZA circuit was constructed using the following parts: a OP999 photodiode, a 22pF capacitor, a 180kΩ resistor, and finally an LF356 operational amplifier with ±12V rail voltages. An IR LED was used, with a series 50Ω resistor, as the light source that was driven with a 5V, 20kHz square wave. The output voltage was 8V$_{pp}$ with a cutoff frequency of 41kHz. An important lesson about the behavior of non-ideal op amps was displayed with the inclusion of the capacitor to keep the op amp stable.

A References

[1] N.W. Emanatoglu ”Lab #1; photodetector and transimpedence amplifier,” University of Maine, Orono, ME, 2017.

[2] D.E. Kotecki ”Lab #1,” University of Maine, Orono, ME, 2017.

[3] Cree 5-mm Blue and Green LED. Cree, 2017.

[4] WP7113SGC. Kingbright, 2017, p. 3.

[5] ”PIN Silicon Photodiode”, 2017. [Online]. Available: http://web.eece.maine.edu/ kotecki/ECE342/datasheets/OP993-999_0.pdf. [Accessed: 24- Sep- 2017].

[6] WP7113SEC/J3. Kingbright, 2017, p. 3.

[7] IR1503. EVERLIGHT, 2017, p. 4.