Transimpedance Amplifier for Polymer Photodiodes

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Abstract

Dr. Braun's students in the Polymer Electronics Lab currently have a way to measure the light intensity from their light emitting devices however it consumes an unnecessary amount of space and power. I offer to improve upon the existing transimpedance circuit that Dr. Braun currently uses, reducing the total space occupied by the circuit and the power consumption of the current setup. The transimpedance circuit measures the incidence light intensity from the polymer-based photo detector and outputs an accurate, discrete, and measurable voltage. The current setup however utilizes two 20V wall warts for the positive and negative rails of the transimpedance amplifier. I plan to reduce the two 20V wall warts to a single 12V wall wart. Because of this, difficulty arises from both producing accurate voltage values near the negative rail, or ground, using a single supply, and from measuring the light intensity accurately without additional readings from noise and bias offsets. The current produced from the photo-sensor ranges from pico- to micro- amps, which is a sensitive domain to noise.

Chapter 1: Introduction

Dr. Braun needs a more accurate and physically smaller design for measuring the current produced from a polymer photodiode. The current implementation designed by Rob Point in 1999 [11], utilizes two 20V wall warts for the positive and negative rails of the transimpedance amplifier. This circuit setup consumes an unnecessary amount of space and dissipates power in both the 20V wall warts. I propose to implement only one 12V wall wart to power the transimpedance circuit. In addition, the output voltage of the transimpedance circuit needs to achieve a near zero voltage (approximately down to 100uV) on the output when the photodiode produces little to no current.

A transimpedance circuit measures an input current and outputs an amplified voltage. The current transimpedance circuit measures current from a range of 1.4 pA up to 50uA, and outputs 0.28uV to 10V, with a gain of 200k volts per amperes. It uses a MAX420 chopper amplifier, along with two voltage regulators: one LM7915 positive voltage regulator and LM341-15 negative voltage regulator, both which provide the rails for the amplifier. The photodiode connects to the negative terminal of the Op-Amp while the positive terminal uses a reference voltage from a voltage divided by two resistors, 1M ohm and one 20k ohm pot that divides the voltage from either the positive +18V or -18V rails. The gain of the transimpedance amplifier comes from the 200k ohm resistor connected in an inverting feedback setup. The resistor value determines the gain and needs to stay above 200k.

The current setup for this circuit needs a few adjustments in components. For example, the MAX420 chopper amplifier might have to change to another op amp that outputs rail to rail voltages. Generic op amps characteristics have an output limit two to three volts away from the rails. I considered using a rail-to-rail amplifier, however most of those can only reach to 100-200mV of the rails. That causes a problem for producing a near zero voltage output. Instead, I plan on using a single 12V wall wart to provide both the positive and negative rails of the amplifier.

Completing this project shows a way to give precise and accurate readings from a photodiode, transforming the current it produces to voltage with an accuracy of microvolts for a device that produces current values on the range of picoamps to microamps. This project also provides an opportunity to improve upon a design created back in 1999 [11], allowing for the replacement of older parts with some fresh ones.

Chapter 2: Requirements and Specifications

In order to get a sense of what requirements and specifications I need for this project, I observed the current transimpeadance circuit for this task and took the specs from that. This way, I knew what my requirements and specs encompass in order to improve upon the older design [14]. **Table 1** displays the specifications and requirements for my design.

Table 1: Transimpedance Amplifier Specifications and Requirements

Marketing Requirements	Engineering Specifications	Justification
3,7	Uses one wall wart as opposed to two.	The current circuit that Braun has uses a 20V wall warts and -20V wall warts, taking up an a large amount of space in the glove box. Having one is possible to do with a switching capacitor circuit.
5	Design the transimpedance gain for 200k±5%	Performed a Monte Carlo Sensitivity Analysis and the results showed that with a LT1012 varying a capacitor's ESR and the temperature, the gain managed to stay within boundaries.
2	Cost less than 50 dollars for parts to build the circuit.	Purchase Op-Amps online and some components like capacitors and resistors. Did cost estimate using Ford and Coulston's equation from their book[1].
4, 1	Physical volume around 5 in x 1 in x 1 in.	Braun gave me the currently used I-V converter and I measured it using a ruler.
1,3	Input for the photodetector current and Output for the amplified voltage both have BNC connectors.	The light detector connects to the current I-V converter via a BNC and the output of it also connects a BNC to a multimeter.
3, 5	Operates at least at +15 to +40 degrees Celsius.	Dr. Braun mentioned this
3	Maximum continuous operating output voltage/current should surpass or equal to 10V/50uA.	The characteristic limits of the output defined by the customer.
1,3	An external flip switch to turn the power on and off.	The device does not need to constantly draw power when not in use.

Marketing Requirements

1. The system should exhibit simplicity.
2. The system should not use expensive parts.
3. The system should operate with low power.
4. The system should physically occupy a small volume.
5. The system should provide accurate/precise outputs.
6. The system should have strong sustainability.

The requirements and specifications table format derives from [15], Chapter 3.

Table 2: Transimpedance Amplifier for Photodiodes Deliverables

Delivery Date	Deliverable Description
03/17/2014	EE 460 Report
04/14/2014	First Draft Schematic
04/15/2014	Design Review
06/11/2014	EE 461 demo
06/13/2014	EE 461 report
11/06/2014	EE 462 demo
11/07/2014	EE 462 Report
11/20/2014	Sr. Project Expo Poster
12/10/2014	ABET Sr. Project Analysis

Gantt Chart:

The Gantt Chart shown in **figure 1** helps me to plan how much time each goal in completing my project may consume. First, I brainstormed a list of steps for myself that were required for the completion of the amplifier, then estimated how long each step would take. The total time starts from the beginning of Winter of 2014 and ends in Fall of 2014. I estimated the times for each goal using the formula provided by R. Ford and C. Coulston[12]. The following shows the formula:

$$Time\ Estimated = \frac{Time_a + 4Time_m + Time_b}{6} \qquad (1)$$

Where: $Time_a$: Pessimistic amount of time it takes to complete a goal.
$Time_m$: Realistic amount of time it takes.
$Time_b$: Optimistic amount of time.

For the more detailed version of my Gantt chart, please use the following URL:
https://app.smartsheet.com/b/publish?EQBCT=c546f91e9dfc43f8972a41637cff0c66

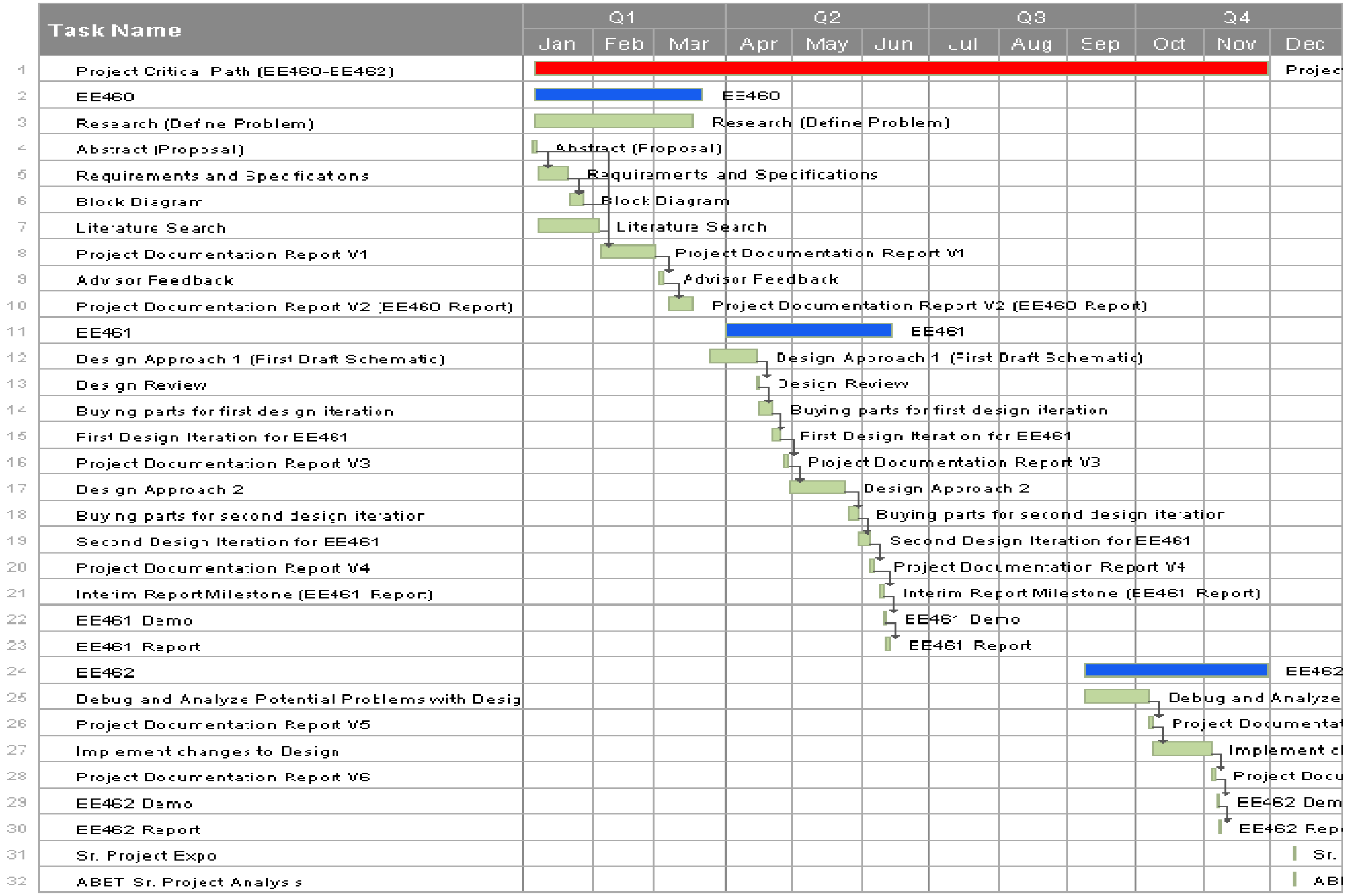

Figure 1:Gantt Chart for Polymer LED Brightness Measurement Circuit

Cost Estimates:

In order to estimate the total amount I might spend on this project, I used the formula provided by the [13] R. Ford and C. Coulston book *Design for Electrical and Computer Engineers* on page 205. The following shows the formula:

$$Cost\ Estimated = \frac{Cost_a + 4Cost_m + Cost_b}{6} \quad (2)$$

Where: $Cost_a$: Pessimistic total Cost of the parts.

$Cost_m$: Realistic total Cost.

$Cost_b$: Optimistic total Cost.

The data shown in **Table 3** results from using the equation for Cost Estimated.

Table 3: Transimpedance Amplifier Parts Cost Estimates

Anticipated Costs				
What items to purchase	Cost Pessimistic ($)	Cost Realistic ($)	Cost Optimistic ($)	Cost Estimated ($)
Operational Amplifier x2	8	5	2	5
LM7915	3	2	1	2
Multipurpose PCB	6	5	3	4.833333
Wall Wart (12V)	10	7	4	7
Aluminum Housing	20	15	10	15
Miscellaneous Parts	30	18	10	18.66667
Total Cost Estimated				52.5

The justification for these anticipated parts costs comes from the price ranges for similar products online at Digikey. Digikey has all the parts I intend to purchase, making the part prices more accurate for my own project. The total cost amounts to a measly thirty seven dollars and fifty cents, however I only have to implement a circuit on a multipurpose breadboard including powering it with a wall wart so the project does not demand much. The real resource consumed comes from my time spent on this project.

The labor cost estimated to about $13500. The hours per class require 30-35 hours per unit. EE460 requires two units, EE461 three units, and EE462 two units. Totaling up the units and multiplying 30-35 hours, I estimate the number of hours spent on my project to take 210-245 hours. If I work for $25 per hour, then the total labor estimate sums up to $5250-$6125.

Chapter 3: Design Steps

Functional Decomposition of the Transimpedance Amplifier

The following functional decomposition comes from R. Ford and C. Coulston book *Design for Electrical and Computer Engineers* [12]. **Figure 2** shows the level zero block diagram of the transimpedance circuit. The diagram displays and defines the inputs, the outputs, and the basic functionality of the whole system. It does not show any detail on how the system produces the results, only that it needs to.

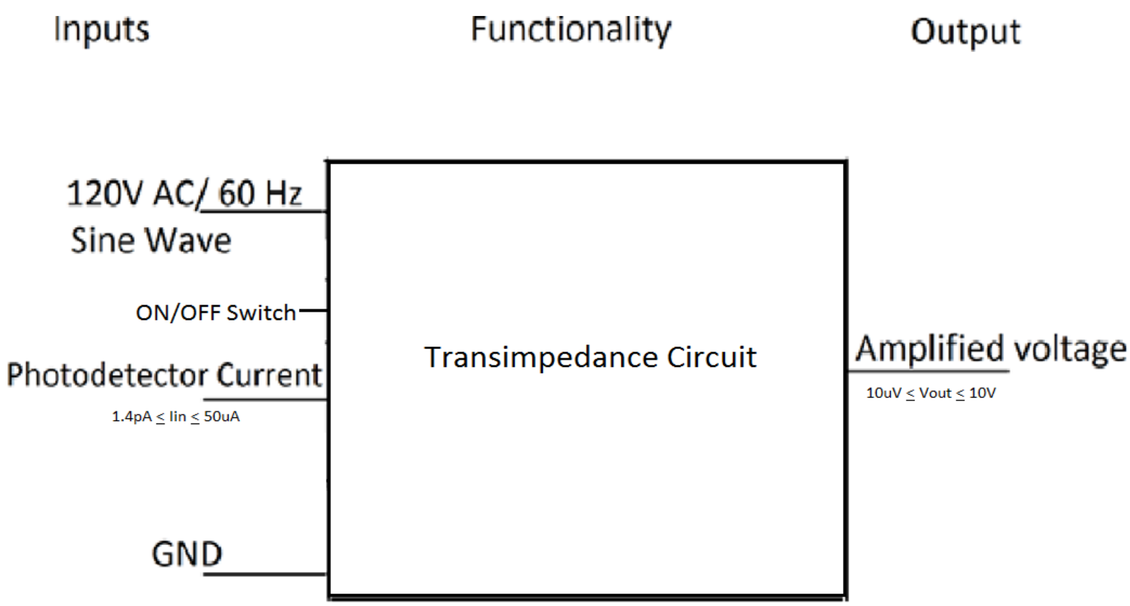

Figure 2: Level Zero Block Diagram

Table 4 shows the table of functionality, which defines the inputs, outputs, and functionality as well.

Table 4: Level Zero Transimpedance Circuit

Module	Transimpedance Circuit
Inputs	120V AC/60Hz sine wave, Photo detector Current, , ON/OFF Switch, GND
Outputs	Amplified Voltage
Functionality	Converts the incoming photodetector current and outputs a discrete, amplified, measurable voltage.

The level one block diagram offers a more detailed look at the sub-functions of the design and lists all the top level modules the design includes. **Figure 3** and **Tables 5, 6, 7, and 8** all show the inputs, outputs, and functionalities of each module.

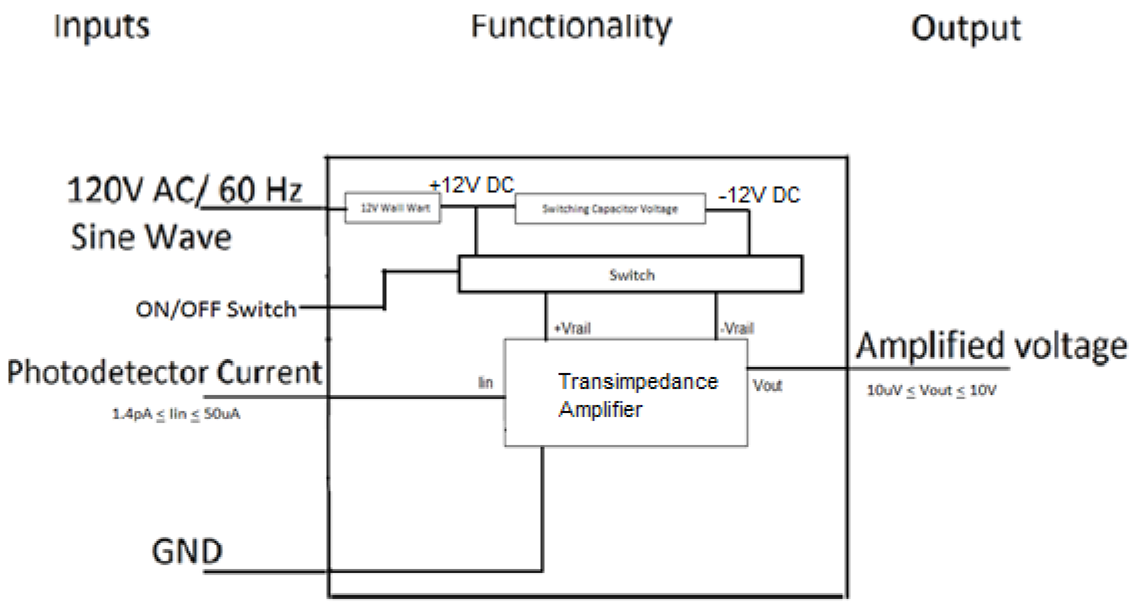

Figure 3: Level One Block Diagram

Table 5: 12V Wall Wart

Module	12V Wall Wart
Inputs	120V AC/60Hz sine wave
Outputs	+12V DC
Functionality	Takes the input signal (120V AC/60 Hz sine wave) from a wall outlet and coverts it to a 12V DC Signal.

Table 6: Switching Capacitor Voltage

Module	Switching Capacitor Voltage Regulator
Inputs	+12V DC
Outputs	-12V DC
Functionality	Takes the magnitude of the input and outputs an inverse signal.

Table 7: Switch

Module	Switch
Inputs	ON/OFF Switch, +12V DC, -12V DC
Outputs	+Vrail, -Vrail
Functionality	Determines whether to allow the DC signals to pass through.

Table 8: Transimpedance Amplifier

Module	Transimpedance Amplifier
Inputs	+Vrail, -Vrail, Photo detector Current, GND
Outputs	Amplified Voltage
Functionality	Converts the incoming photodetector current and outputs a discrete, amplified, measurable voltage.

Simulation

Next, I used LTSpice to simulate the circuit I had designed. The device had to have a gain of 200k ±5%. First, I simulated the circuit for its nominal performance. I calculated the gain as shown:

$$Gain = \frac{V_{OUT}}{I_{IN}} \qquad (3)$$

Assuming it had a current of 50uA input, the voltage should equal 10V for a gain of 200k. **Figure 4** and **Figure 5** both display the circuit and its nominal performance. The transient response in **figure 5** shows the current increasing and as a result, the voltage magnitude increasing also, as expected. The current source connected to the inverting input of the LT1012 in **figure 4** turns on after 1.5ms and increases from zero to 50uA. That causes the curve shown in **figure 5** to occur, slowing down once the steady state voltage of 10V has been obtained.

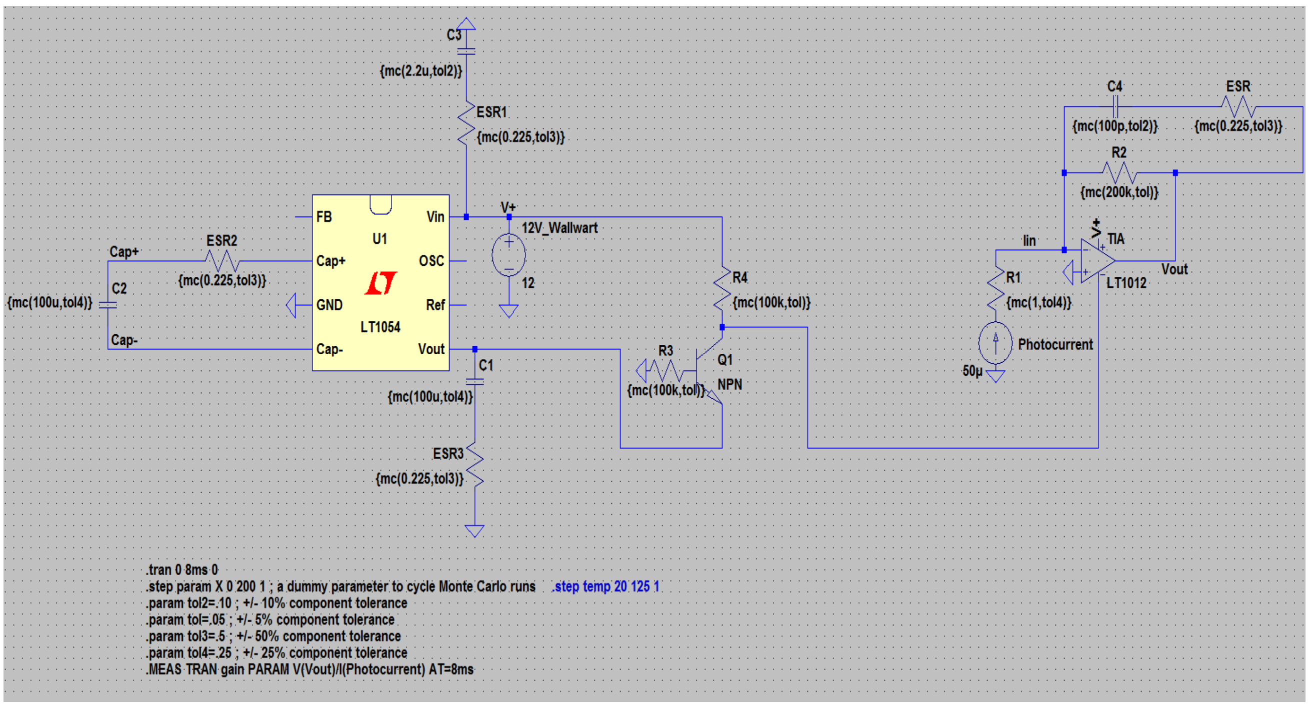

Figure 4: LTSpice Circuit for Simulation

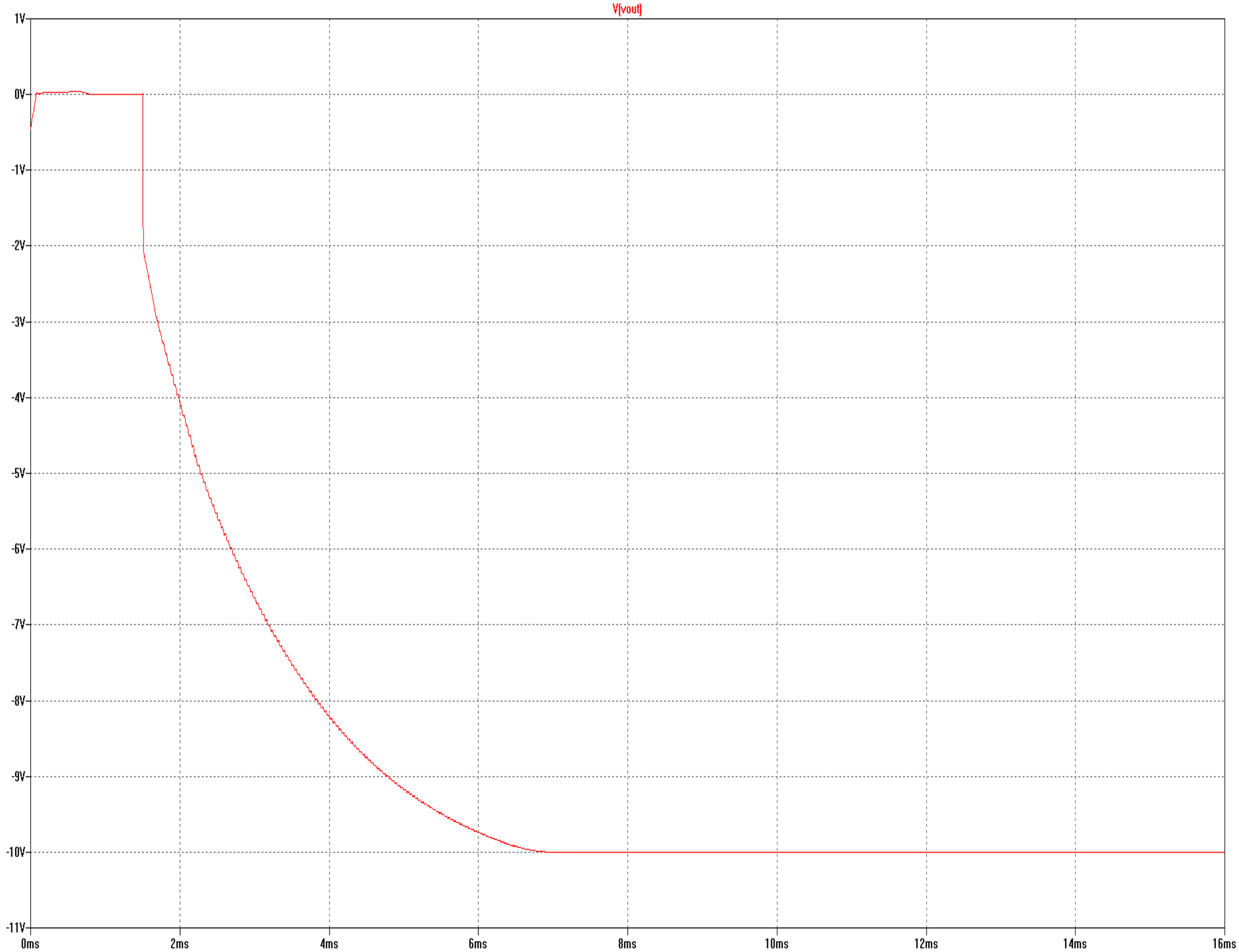

Figure 5: Nominal Output for a transient input current of 50uA

After showing the circuit operated properly, I performed a Monte Carlo sensitivity analysis and tested the circuit three different ways: varying component tolerances, temperature, and parasitic components and their tolerances. For the component tolerances, I gave the resistors a tolerance of 5% while giving the capacitors a tolerance of 25%. I looked at products for these components online to simulate their values to achieve results that come close to their real world counterparts. For the temperature, I set the coefficients of the components to 50x10^-6 and varied the temperature from 20°C to 125°C with steps of 1°C. These extreme values offer a larger picture of the behavior of the circuit, albeit the temperature of the circuit most likely will not reach these values. Finally, I included the parasitic values in the previous two simulations since varying temperature and component tolerances also affect their parasitic values. **Figure 6 and 7** show the results of the Monte Carlo sensitivity analysis. The simulation ran 200 times and using Excel, I plotted the results in a histogram. The most common gain value equaled 194k, which composed 12.5% of the 200 runs. The end points of the gain range from ±10% and the results land within ±5%. This means that our circuit runs within the specified boundary of ±5% and works successfully.

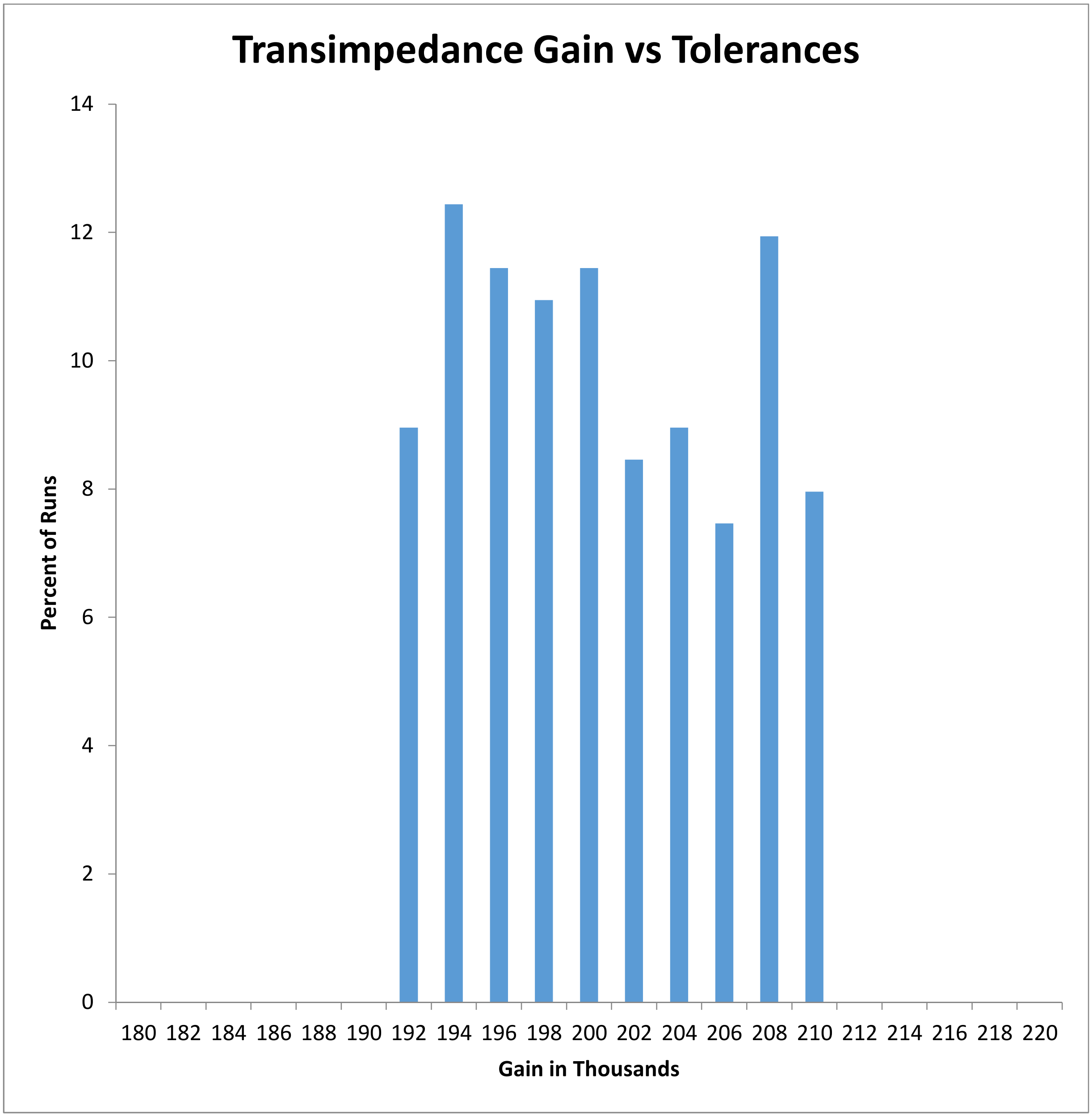

Figure 6: Histogram of Transimpedance Gain with varying tolerances

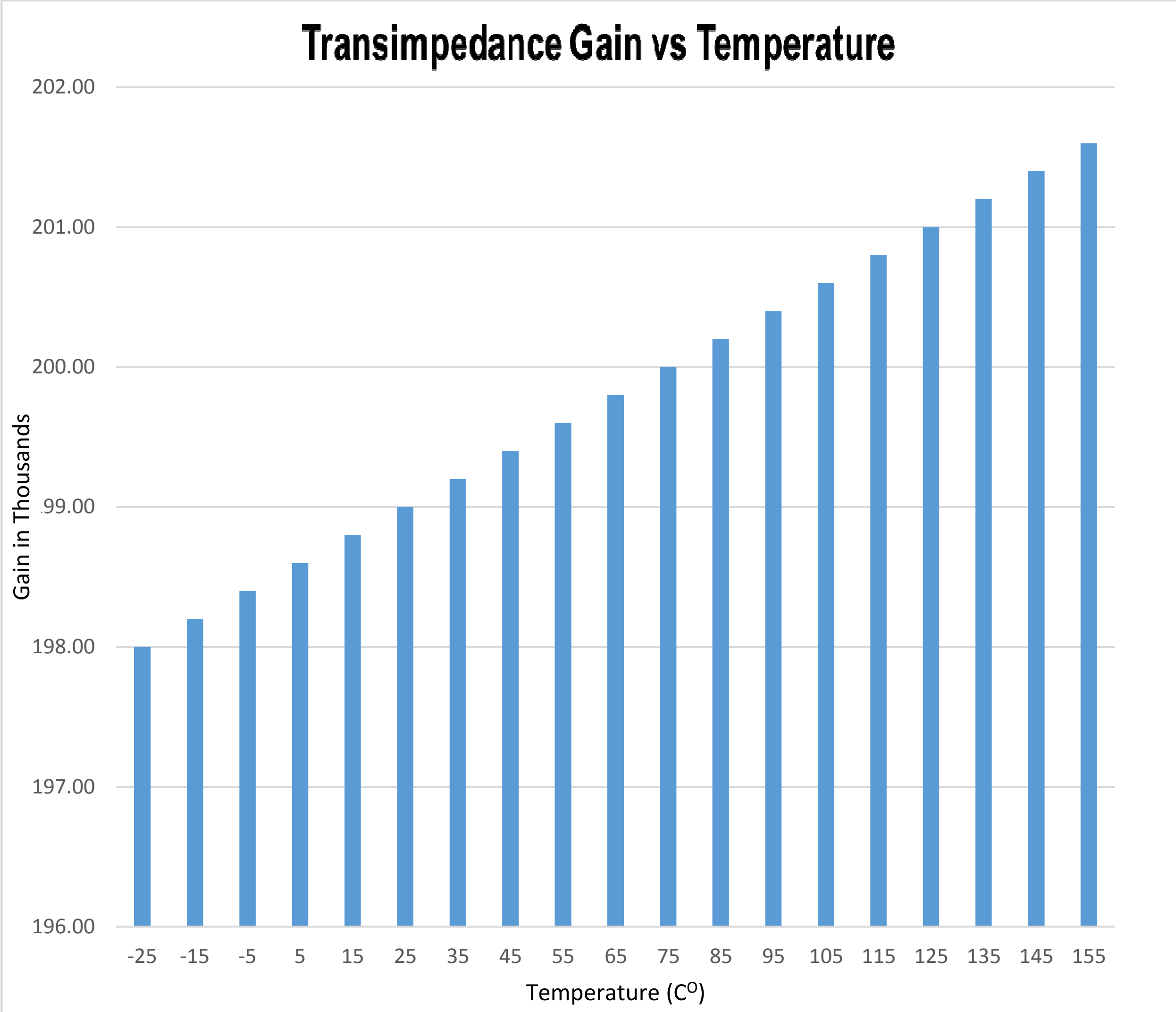

Figure 7: Histogram of Transimpedance Gain with varying temperature

We see that in **Figure 7**, the variation of temperature has a linear effect on the gain. As the temperature increases, the resistor in the inverting feedback increases, thus increasing the gain. We see that the gain also stays within ±5% meaning this circuit can also withstand a wide range of temperature variations as well.

Appendix B contains the netlist for the simulation.

Chapter 4: Construction and Testing

After simulating the results, I bought the necessary components to build the circuit. I searched online and found the following list of parts from Linear Technology, Digikey, Mouser, MPJA, and Radioshack:

- 3x 100uF
- 2x 0.1uF
- 2x 10uF
- 2x 100k Ω
- 1x 200k Ω
- 1x 10k 15-Turn Potentiometer
- 1x LT1054
- 1x LT1012
- 1x 12V Wall Wart
- 1x 12V Wall Wart DC Jack
- 1x Perf Board
- 1x Bread Board
- 1x 3”x2.2”x0.9” Aluminum Diecast House
- 1x 2N-3904 NPN Transistor

Using a breadboard, I built the circuit part by part in the Senior Project Lab of the EE Department. I first built the transimpedance circuit by itself. I used the duel power supply instruments provided by the university to provide positive and negative 12V rails. I also borrowed a solar cell and some connectors from the Senior Project Lab. I used the circuit provided by LT in the datasheet for the LT1054 chip. The switched capacitor provides a negative rail for the op amp since our design only uses one +12V wall wart. The negative rail plays an essential role since the circuit inverts the output. I built the switching capacitor circuit as in **figure 4** and to quiet the noise on the rails, I placed a polarized 10uF bypass capacitors on the positive and negative terminals.

After constructing the switched capacitor, I measured the output voltage with the Agilent oscilloscope and saw that it provided -12V as expected. For the next steps, I plugged in the 12V Wall Wart Connector to the board and connected the transimpedance circuit with the switching cap circuit. When I measured the output, it displayed a gain of 200k. **Figure 10 - 11** show the finished circuit on the breadboard and the output waveform.

The first time I turned on the rails, the output of the circuit gave me incorrect values. The output immediately railed at -11V. I realized that I made a mistake. When I measured the current flow from the solar cell, I measured the current flowing into a 10k resistor by itself, thinking that the same current flowed into the circuit as well. But the circuit that I have in **figure 4** does not have an input resistance, thus the input impedance appears zero due to the virtual ground caused by the feedback setup. This meant that the current flowing into the circuit differed greatly from what I had expected. In order to accommodate for this, I added a 10k 15-Turn potentiometer. Braun accepted a 10-Turn pot for this project, but preferably a 100. The potentiometer worked and I measured the current using a

Keithley as an Amp meter and the voltage off the Agilent oscilloscope. I varied the resistance of the potentiometer and produced the results in **table 9**. As I observed the output, I noticed a ± 20mV noise in the output waveform. At first I tried to adjust the feedback capacitor by increasing its value from 100pF to 2.2uF, however this overdamped the response and the transient state lasted for about three seconds. I spoke with Braun and he informed me that a 0.1uF could replace the 2.2uF instead. He also mentioned that the invisible flickering of the lights in the lab caused the noise to appear on the output waveform. The lab uses high frequency lights that turn on and off, which our eyes cannot detect but the solar cell can. Another factor to consider came from the connectors I borrowed from the lab. They need bypass capacitors as well in order to mitigate the noise they generated.

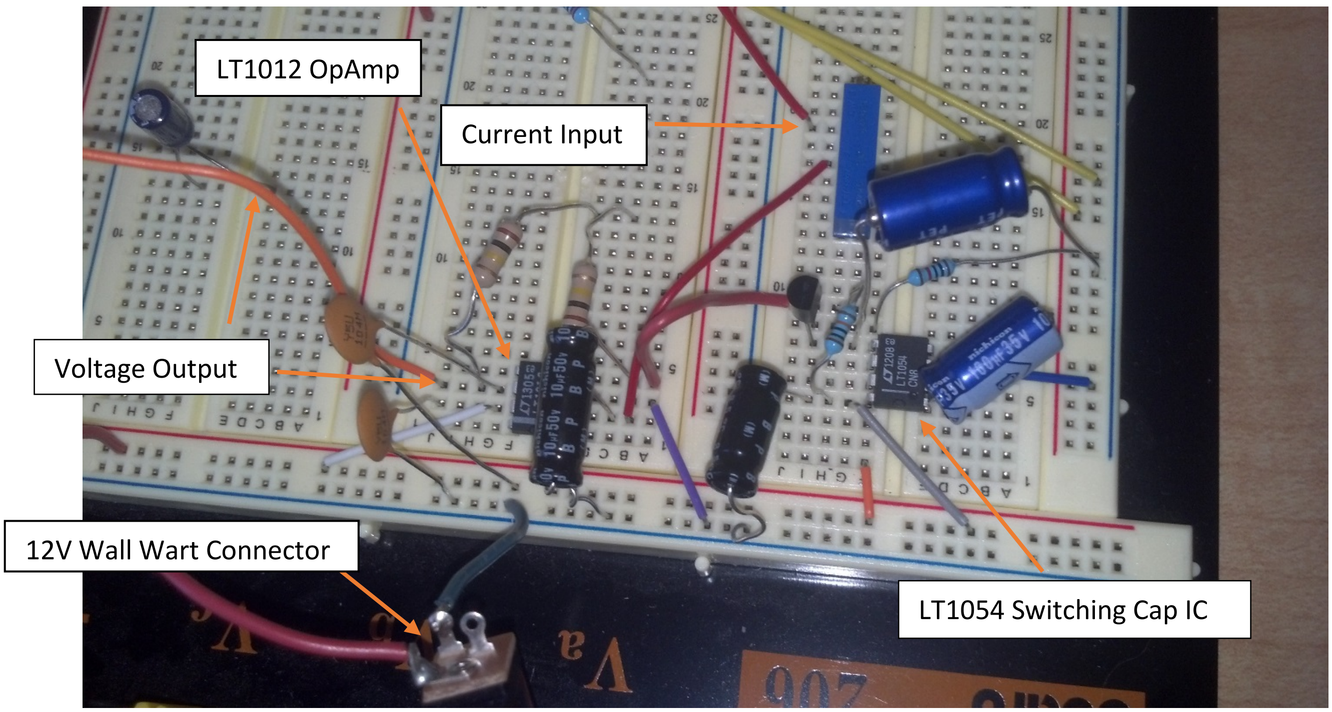

Figure 8: Transimpedance with Switching Capacitor on Breadboard

Table 9: Results of Gain

Current Solar Cell (uA)	Voltage Vout (V)	Gain (Volt/Amp)
18.8	-3.75±25mV	199468
19.5	-4±20mV	205128
39.4	-7.93±22mV	201269
50.5	-10.125±20mV	200495

I needed an aluminum housing to shield the circuit not only from external noise sources but so that Dr. Braun may use the circuit inside a glove box for his polymer electronics lab. The glove box is a clean box where nitrogen gets pumped into and can build a lot of static charge on an object given it doesn't conduct very well. The aluminum housing conducts enough to avoid accumulation of charge. The housing also needs to occupy a small amount of space, similar to the current box shown in **figure 11**. When the housing goes inside the glove box, it shouldn't get in the way of lab experiments when trying to move things about inside the box. The perf board used for the circuit also determines the minimum size of the house. I found an optimal perf board (5"x2") from radio shack that had copper traces drawn down from one side to the other length wise which I used to provide GND and +12V to my circuit.

Finding an aluminum housing took approximately three days to do. I searched online at first through the websites Mouser, Digikey, and Hammond but I did not find a house with the correct dimensions. I had a problem finding a house with the same dimensions or a little bigger. Finally, I found a aluminum house from the website MPJA with the dimensions 3.1x2.2x0.98". I looked elsewhere online but only found houses that jumped up to sizes around 4x3x1.5", which unnecessarily occupied large amounts of space in the glove box. This also meant that I had to modify the perf board so that it would fit as well.

Once I finished testing on the breadboard, I disassembled the circuit and build my first circuit prototype shown in **figure 9**:

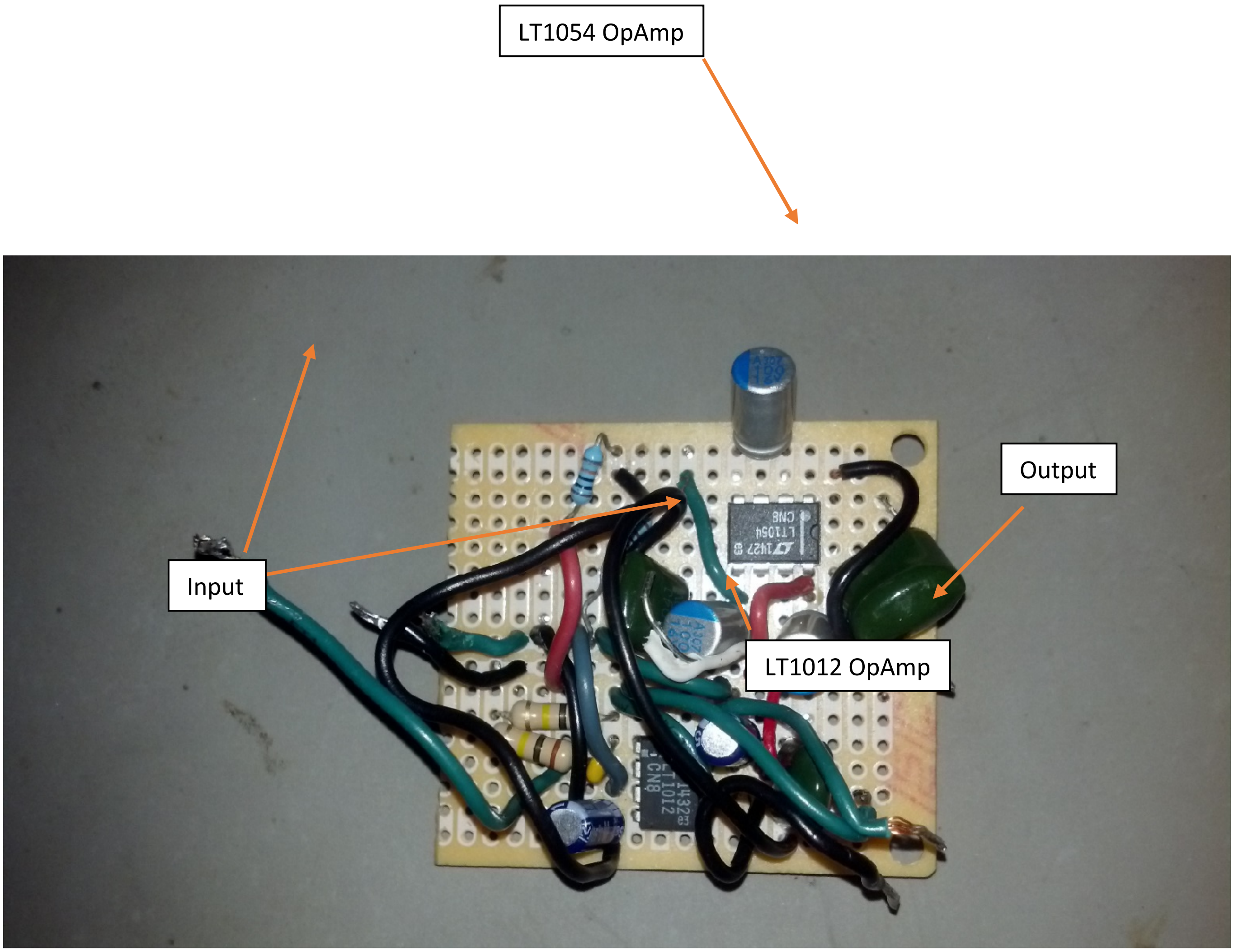

Figure 9: First design of the Transimpedance Circuit

This first design could take in a current input of 50uA and output 10V but the wires seen in the photo made it a tight fit when placed inside the aluminum box and covering it with the top. These wires also became sources of noise in the circuit. **Figure 10** shows the output waveform at 10V with a noise of 200mVpp. This was too much noise for specifications, the voltage was not close enough to zero volts when there was little to no current. Also, when I placed it in the box, the strain from pushing it into the box caused some wires from the bottom of the perf board to pop out due to some poor solder connections made. When I soldered the components in, I used a high power iron, 50 Watts, which dissipated too much heat and lifted the copper traces, weakening the ability of solder to make a good connection with the board. Dr. Braun advised me to redo the circuit again so that when placed inside the box, it would fit nicely and not have much noise.

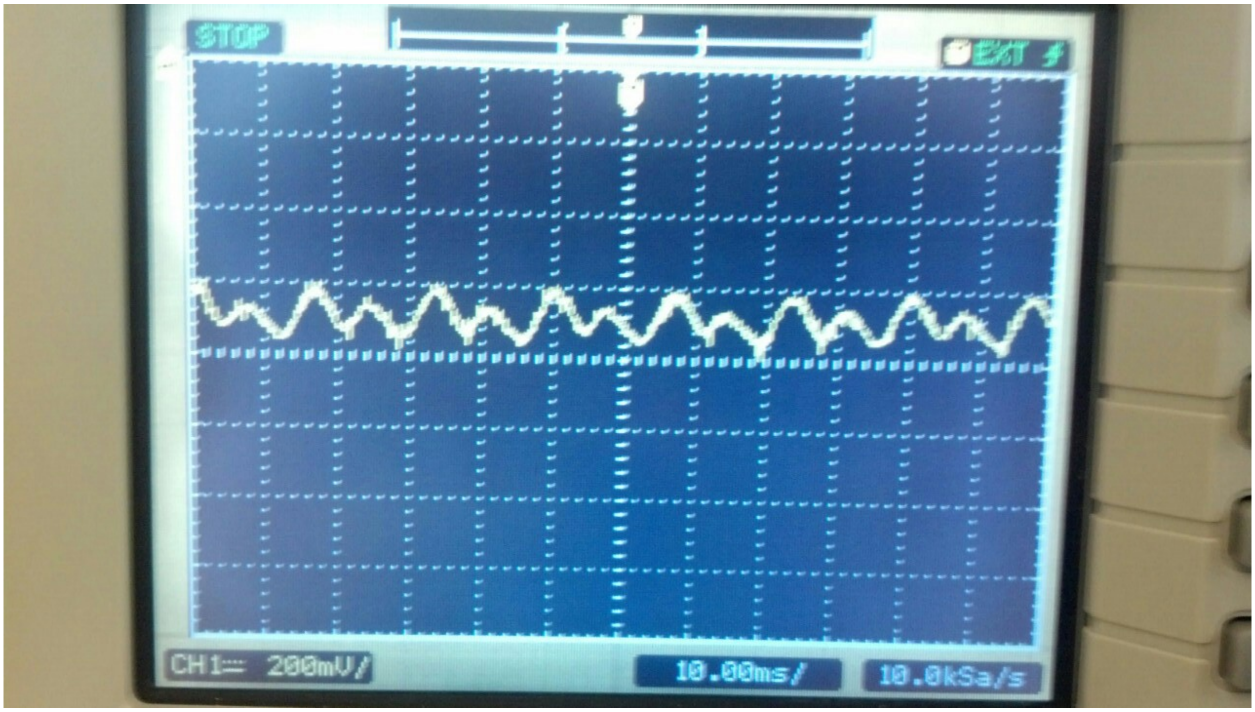

Figure 10: Output wave form of first prototype with noise

When making the second board, I took some things into consideration. I wanted to keep the noise levels down on the output as much as I can. When I asked Braun how to do this, he told me to minimize the number of wires, the loops in wires, and he showed me that two bypass capacitors near the supplies of both chips (LT1054 and LT1012) would help eliminate unwanted noise. When you have two bypass capacitors in parallel, their effective impedance divides down. This allows for the capacitors to provide little impedance as the frequency increases. Theoretically, all capacitors become shorts at high frequency, however in reality, these components have a resonant frequency where they behave more inductively as frequency increases. So by using two bypass capacitors, I increased the resonant frequency point, allowing for a lower impedance at high frequency. On the rails of both ICs, I had originally placed a 100uF and a 0.1uF capacitor in parallel. However, when I tried this on the switching capacitor IC LT1054, the output became unstable. When placing an extra, non-polarized, capacitor at the supply input of the LT1054, I read the datasheet for it and found that it had discharged the output capacitor on the circuit, causing the voltage at that node to fluctuate from -12V to 0V. So I replaced the polarized 100uF and the non-polarized 0.1uF with a single polarized 10uF instead. The datahsheet called for a polarized capacitor so I left the 10uF instead because I did not have enough space nor caps for an extra polarized bypass capacitors. I also added an extra polarized 10uF capacitor to the output of the LT1054 to quiet the noise. **Figure 11** displays the current circuit used in the polymer lab and **figure 12** displays my finished board in the housing. Afterwards, I connected the circuit in the polymer lab to a

Keithley236 as a current source and professor Braun and I recorded some data points to determine its linearity using a DMM Agilent 34401A. **Table 10** and **figure 13** display the results.

Figure 11: Rob Point's circuit

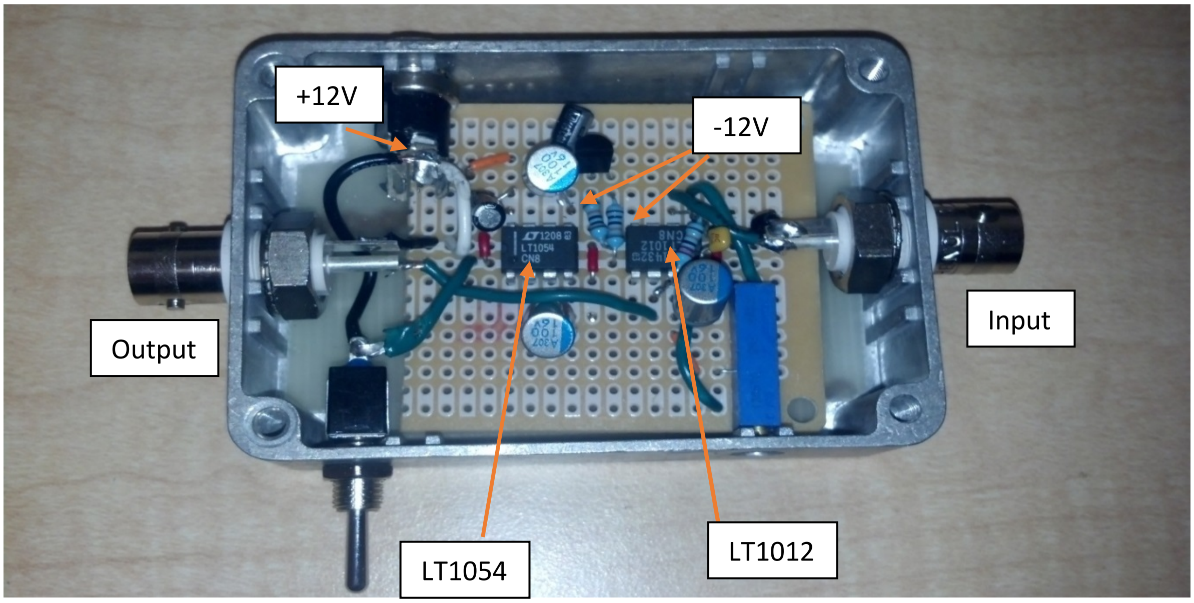

Figure 12: My finalized circuit

Table 10: Results from Keithley236

Input Current	Output Voltage (Negative Volts)	Gain
100pA	50uV ± 1uV	500000
200pA	72uV ± 2uV	360000
500pA	138 ± 1uV	276000
1nA	250uV ± 1uV	250000

2nA	471uV + 1uV	235500
5nA	1.140mV + 1uV	228000
10nA	2.252mV + 2uV	225200
20nA	4.477mV + 2uV	223850
50nA	11.164mV + 1uV	223280
0.1uF	22.035mV + 2uV	220350
0.2uF	44.067mV + 2uV	220335
0.5uF	110.138mV +2uV	220276
1uF	219.99mV	219990
2uF	439.78mV	219890
5uF	1.0991V	219820
10uF	2.200V	220000
20uF	4.398V	219900
50uF	10.993V	219860

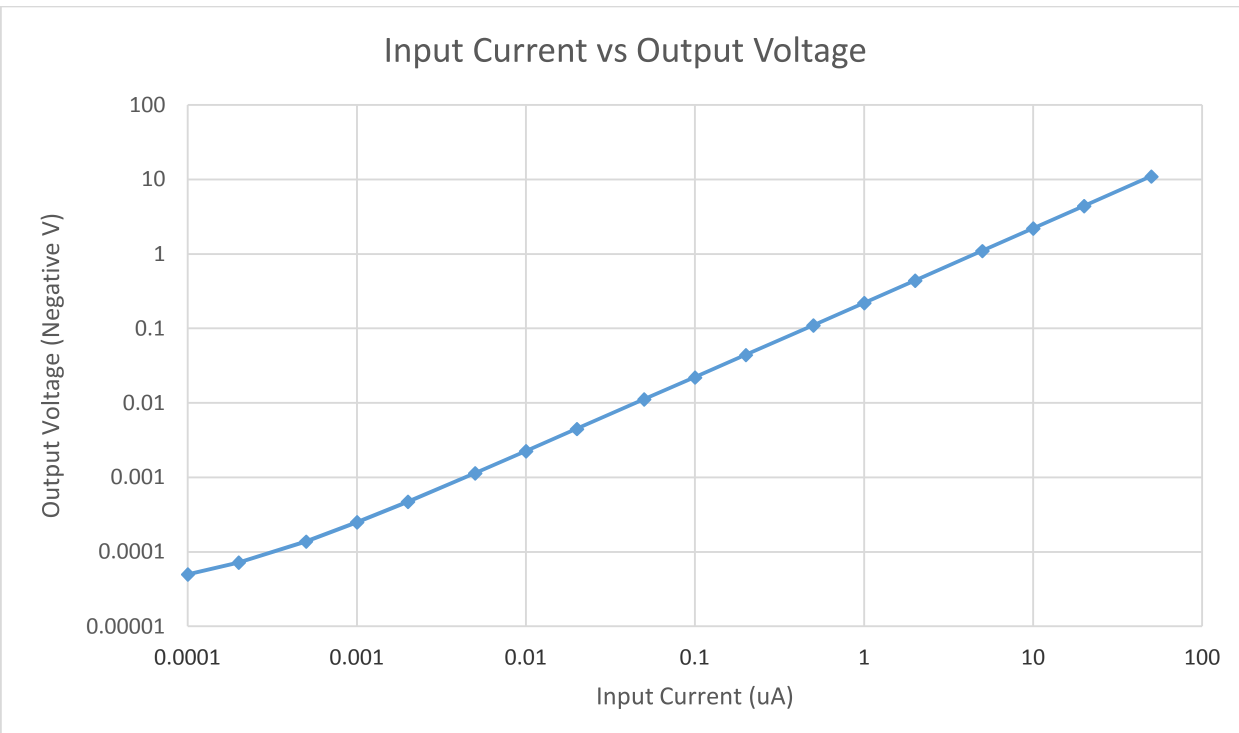

Figure 13: Log Scale of Current Input to Voltage Out

Chapter 5: Conclusion

Overall, the circuit met the required specifications. It produced a quiet output response with noise ranging from 1-2uV as shown in **table 10**, much less as the breadboard noise results of 20mV. The combination of the shielding and the gain seemed on average 220k , a 10% higher gain than the specified value 200k. The resistor tolerance explains the gain discrepancy as it actually measured out to be 219.869k ohms. I used a one 200k ohm resistor instead of two 100k ohm resistors when building my second circuit design to minimize how much space the circuit occupied.

There are some possible improvements for this project. Designing a PCB board saves space as one could design the board for a smaller housing (maybe a 2x1x1") and not use any wires that create noise in the circuit. This would also consume less power as the wires dissipate power. Also, the LT1012 amplifier is not specifically designed for a transimpedance purpose, however the results produced meet specifications.

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[15] Linear Technology, *LT1012A/LT1012 PicoAmp Input Current Microvolt Offsent Low Noise Op Amp*, 2014, [Online], Available: http://cds.linear.com/docs/en/datasheet/1012afbs.pdf

Appendix A – Analysis of Transimpedance Amplifier for Polymer Photodiodes

Project Title: Transimpedance Amplifier for Polymer Photodiodes

Student's Name: Sheridan Knighton

Student's Signature:

Advisor's Name: David Braun

Advisor's Initials:

Date: December 12, 2014

• 1. Summary of Functional Requirements

Describe the overall capabilities or functions of your project or design. Describe what your project does. (Do *not* describe how you designed it).

The transimpedance amplifier circuit receives an input current produced from a photodiode and transforms that reading of current into an amplified, discrete voltage reading. This voltage value dictates how Dr. Braun's Lab students calibrate their polymer electronic device while utilizing minimal power cost.

For list of functional requirements, refer to Table 1 of chapter 2.

• 2. Primary Constraints

Describe significant challenges or difficulties associated with your project or implementation. For example, what were limiting factors, or other issues that impacted your approach? What made your project difficult? What parameters or specifications limited your options or directed your approach?

Trying to get an Op-Amp that would output a voltage around 10uV with a single supply proved difficult. At first, I tried looking for a rail-to-rail Op-Amp online in vain. In response to this difficulty, I asked a professor at the University for a type of circuit that could power a Op-Amp with a single supply. He told me to use a switching capacitor voltage regulator to provide split supply with a single one. We must also excessively filter the voltage output of the switching capacitor to provide a clean signal. Without filtering, the output of the switching capacitor becomes heavily corrupt with noise, causing undesired results.

Fitting all the transimpedance amplifier components onto a 3"x2" breadboard was difficult at first. I doubted that I could make the circuit small enough to operate without a lot of jumper cables, which is what happened in my first iteration of the circuit. Those wires created a lot of noise that ranged up to 200mV. I had to purchase a whole other set of parts to rebuild the circuit. Both the physical limitation and noise specification directed me to build a smaller sized circuit, placing the integrated circuits efficiently on another perf board.

• 3. Economic

• What economic impacts result? Consider:
  Human Capital – What people do.
  Financial Capital – Monetary instruments.
  Manufactured or Real Capital – Made by people and their tools.
  Natural Capital – The Earth's resources and bio-capacity.
• When and where do costs and benefits accrue throughout the project's lifecycle?

• What inputs does the experiment require? How much does the project cost? Who pays?
Original estimated cost of component parts (as of the start of your project).
Actual final cost of component parts (at the end of your project)
Attach a final bill of materials for all components.
Additional equipment costs (any equipment needed for development?)
• How much does the project earn? Who profits?
• Timing
When do products emerge? How long do products exist? What maintenance or operation costs exist?
Original estimated development time (as of the start of your project), as Gantt or Pert chart

Actual development time (at the end of your project), as Gantt or Pert chart
What happens after the project ends?

Human Capital: I work on designing a lower power solution to the current implementation along with my advisor Dr. Braun who helps me when I run into obstacles. Dr. Braun plans on having his students utilize this transimpedance circuit to calibrate their polymer electronic devices. In order to build this project, manufacturers must design and create a myriad of integrated circuits and parts needed specifically for this detector. Buying parts incentivizes advertisement companies to focus marketing that particular product, and delivery laborers convey parts I ordered to their destination. The EE Department technician, Jaime, also helped me to drill holes into the aluminum housing for my circuit as I am not licensed to use the tools.

Financial Capital: Cal Poly can reimburse me up to 100$ that is spent on my senior project. When I make the purchases, I save the receipts and show it to the EE Department. LTSpice has a free software instrument that I can utilize. I saved enough money from working over the summer to purchase the parts as well.

Manufactured or Real Capital: Parts developed by designers with their software tools such as LTSpice, MatLab, LabView, etc. These help me design and analyze a hypothetical schematic before actual implementation. Agilent, Keithley, and HP measuring devices such as their oscilloscopes, multimeters, function generators, and power supplies provided by Cal Poly. These help me perform accurate measurements such as desired voltage levels and power efficiency. I also had to ask someone to use a drill for the holes in the aluminum housing so that I could place the DC Power Jack, potentiometer, and a SPST switch.

Natural Capital: Making these parts requires silicon for the chips, PCBs requires copper and substrates like duroid. The wires used are made from copper. Soldering the components require rosin or lead onto a plastic perf board. The aluminum needed to make the housing for my circuit and BNC connectors.

The costs accrue when I have to start buying parts and equipment for building the project. This occurred during any of the design iterations that I labeled in the Gantt Chart. The benefits accrue during the design iterations stages as well. Performing rigorous research on the topics that project covers, mostly analog, helps me design a better first schematic and improve upon that later on.

The inputs the experiment requires 120VAC, photodetector input current, and a switch to turn the device on and off. The project costs in terms of parts, around $40 and the labor approximates to $13500 for the critical path project. I can either pay parts costs, or ask the EE Department for funding for parts up to at least $100 assuming I save my receipts. The project needs a 120VAC source, costing the school electricity. Oscilloscopes and other additional equipment tools do not cost anything since the school provides these items.

The actual cost of the project was around $60 since I purchased a complete set of parts twice, not to mention extras in case anything got damaged. See attached receipt for more details.

Dr. Braun, his students, and I profit from this project. This project allows the students and Dr. Braun to measure and calibrate their light emitting polymer devices. I profit from this because I gained experience in not only designing a product with software and seeing it to implementation, but also in managing and project planning which both prove incredibly useful in the future for almost anything.

Products emerge after the first design iteration and last for ten years, or until Dr. Braun has a new student develop a more superior design. The maintenance costs for this project potentially arise from replacing parts, likely the Op Amp or Switching Capacitor Voltage Regulator. The operation costs consume electricity, less than ten watts of power.

The actual time taken to finish the project is shown in **figure 13** as a Gantt Chart on the next page.

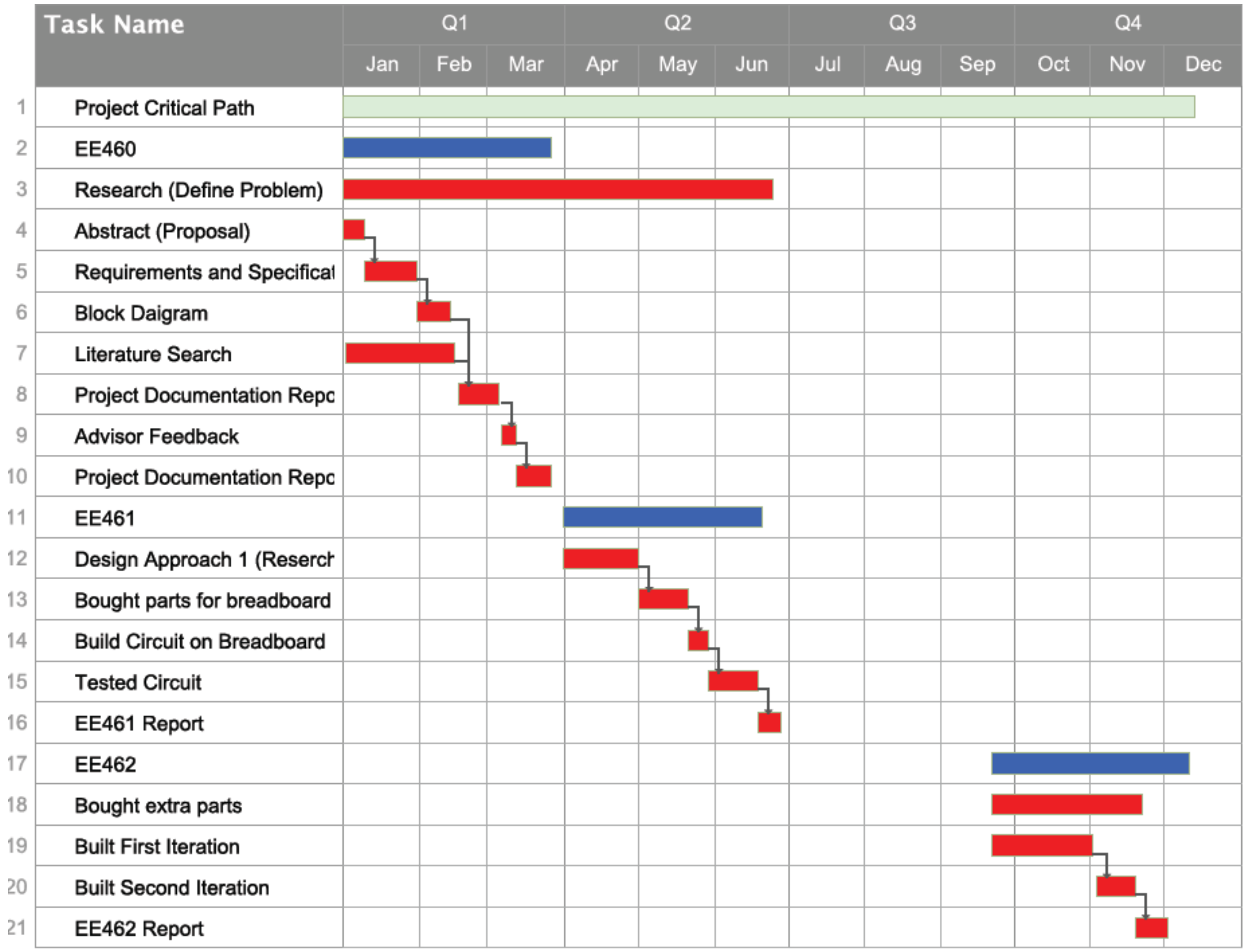

Figure 14: Actual Developmental Time

After completion of the project, Dr. Braun will use it for the next 20 years or until someone else improves upon my design. If it fails before then, Dr. Braun has other transimpedance amplifer circuits that he can use.

• **4. If manufactured on a commercial basis:**
• Estimated number of devices sold per year
• Estimated manufacturing cost for each device
• Estimated purchase price for each device
• Estimated profit per year
• Estimated cost for user to operate device, per unit time (specify time interval)

Refer to Chapter 2, page 5 for the parts and labor cost estimates.

The number of devices sold per year would approximate to 1460 units since I estimate that once I settle on a final design, I could make 5 units a day by hand, each taking about 2 hours. The manufacturing cost would accrue up to $50x1460 = $73,000. I would set the price at $90 to compensate for the supplies and labor I put into this. The estimated profit per year would then sum up to $90x1460 minus $73,000 totaling to $58,400.

• 5. Environmental

• Describe any environmental impacts associated with manufacturing or use, explain where they occur and quantify.
• Which natural resources and ecosystem services does the project use directly and indirectly?
• Which natural resources and ecosystem services does the project improve or harm?
• How does the project impact other species?

The environmental impact comes from manufacturing the device such as making a silicon wafer chip from a factory. The natural resources used directly consume semiconductor materials such as silicon, and conducting material like copper or even germanium. When I asked Jaime to help drill the holes in the aluminum housing, it created some shreds of metal that had to be cleaned up. Soldering the components to the board, there were traces of copper that lifted off and fell that need to be thrown away, as well as strands of wire that I cut from time to time. Indirect resource consumption comes from using different kinds of metal to make a wafer chip of silicon for an IC, the saw composed of diamond to cut the wafer chip, and light in order to develop the photoresist. Finally, for operation of the transimpedance amplifier, it needs light for a photodetector to produce a current so that it can amplify and produce a signal. This project improves upon alternative sources of energy. This can help us wean off from using more polluted sources such as coal or nuclear energy where the waste cannot be so easily disposed of. This project does consume some resources needed for the photo-detectors and ICs but it also helps improves the environment by offering a potential solution of using light as an energy source using polymer based photo-detectors. This project impacts the people, including Dr. Braun, in the polymer electronics laboratory as they need a transimpedance amplifier for their assignments. This project could potentially impact other species as the idea of harvesting energy from the sun rays requires a panel that occupies space in their natural habitat. Although this is a small circuit, on a larger scale building solar cells requires a lot of space and land that isn't inhabited by other species.

• 6. Manufacturability

Describe any issues or challenges associated with manufacturing.

The issue with manufacturing the device comes from fitting and connecting parts bought online to connect securely within the aluminum housing. Some of the parts online do not come in DIP packages but in SOP, SOIP, etc. Another issue comes from the fact that not every part one purchases online gives the same parameters. For example, if I buy two LT1051 Switching Capacitor Voltage Regulators, their parameters differ slightly. Although this does exist, a stronger influence comes from the component variations in the resistors and capacitors. Since the resistor in a transimpedance amplifier determines the gain, if it does not reach 200k or above, the device may not perform within necessary conditions. A potentiometer helps with this problem, however it consumes a little more space and requires more wires to connect to my circuit. Another issue was trying to fit all the components on the board with a minimum number of jumper cables as that would introduce noise into the circuit. When desoldering the components into the perf board, I sometimes kept the iron on the copper trace for too long and the trace would lift and come off completely. This made it incredibly difficult to keep a good solder joint between the component and the board itself. Sometimes the leads of some components would be attached to the copper traces with some small amount of solder. So I try to pull the leads to the side to break that solder connection physically, however it sometimes also pulls off the copper trace as well. Another issue was trying to suck up the solder using a wick as it needed more heat but that would lift the copper if I raised the wattage on the iron. When Jaime drilled the hole for the box, it was quite small and Jaime was worried that the strength of the housing would start to decline as he drilled more holes into it. On top of that, if a hole was drilled incorrectly, then that would require more drilling, thus further reducing the strength of the box. Whenever I left my station for more than 10 minutes, I would turn off the iron but when I came back, it took a while for the iron to heat up (about another 10 minutes) and this consumed time since I tend to walk back and forth between classrooms whether it be asking for help or looking for materials.

• 7. Sustainability

• Describe any issues or challenges associated with maintaining the completed device, or system.
• Describe how the project impacts the sustainable use of resources.
• Describe any upgrades that would improve the design of the project.
• Describe any issues or challenges associated with upgrading the design.

For maintenance, one would have to unscrew the top of the housing, desolder the connections between the perf board and the BNCs, switch, and DC Power Jack, remove the perf board from the housing, desolder the broken components, then solder in the new ones without lifting the copper trace, place the board back in the box, solder the connections to the BNCs, switch and DC Power Jack, and then screw the top on. Improving the design of this project could also come from having a dedicated PCB for this purpose instead of a multipurpose PCB. I did not design a PCB for this project as I wanted to make sure that I had the connections and necessary components listed for this project to work correctly before setting the traces and connections on a board that I could not alter.

For sustainability purposes, this project should last for 20 years or at least until Dr. Braun has another student improve upon my design. It consumes electricity and light to operate, however light is an unlimited source of energy, improving its sustainability. Other resources used for this require the solder to make the connections and aluminum to make the housing, however the housing only needs to be made once and it is done.

• 8. Ethical

Describe ethical implications relating to the design, manufacture, use, or misuse of the project. Analyze using one or more ethical frameworks in addition to the IEEE Code of Ethics.

The IEEE Code of Ethics states in their list "…to credit properly the contributions of others." (#7 of the IEEE Code of Ethics) This applies to me because Rob Point's Design from 1999 influenced my own. This means I should source him as a reference when I design my final schematic. My reason for following this ethical rule comes from the Golden Rule: "Treat others as you would have them treat you." If my work influenced someone else's design, I would like some honorable mention in their work for appropriate credit.

• 9. Health and Safety
Describe any health and safety concerns associated with design, manufacture or use of the project.

One safety concern comes from soldering the parts together onto a multipurpose PCB board. I have to make sure that I do not burn myself in the process and that I do not breathe in the fumes from soldering. Another health and safety concern arises from parts that have and do not have RoHS, so I should look for this label when I purchase parts online.

• 10. Social and Political
• Describe social and political issues associated with design, manufacture, and use.
• Who does the project impact? Who are the direct and indirect stakeholders?
• How does the project benefit or harm various stakeholders?
• To what extent do stakeholders benefit equally? Pay equally? Does the project create any inequities?
• Consider various stakeholders' locations, communities, access to resources, economic power, knowledge, skills, and political power.

The social issues associated with this project affect the direct stakeholders who consist of Dr. Braun, Dr. Braun's students, Texas Instruments, UPS, and I. TI and UPS receive money from me when I purchase the parts online, and Dr. Braun and his students have a device that allows them to calibrate their polymer electronic devices in lab. The indirect stakeholders consists of gas companies like Shell, manufactures of the IC's since I do not conduct business with them directly, and advertisement companies with dynamic agendas changing due to purchases of certain products. All these stakeholders benefit equally by further progressing their interests whether it include profiting, working, designing, or teaching. This project creates an inequity in that it promotes the usage of an alternative source of energy as opposed to other sources such as coal, nuclear, wind, hydro, etc.

• 11. Development

I've learned to start projects early and invest lots of time! Starting work early helps one to find and solve most overlooked problems that could easily stay hidden until the very end of your project's critical path which requires drastic costs for minor changes. Also, ask around for when needed, even outside sources such as people one may know outside of school who have knowledge in the subject.

References

[1] S. Franco, *Design with Op-Amp & Analog Integrated Circuits*, 3rd Edition, McGraw Hill, 2002

Could help my project by helping me with designing and understanding certain circuits needed for creating an efficient I-V converter or other subsystem that will be needed.
This source has authority since it has been cited 828 times, showing that it is very reliable.

[2] Jian Lee, *Advanced Electrical & Electronics Engineering*, Vol 2, Springer Berlin Heidelberg, 2011

Could inform my project by helping me understand more analog circuit knowledge and other I-V converters.
This source has authority since it is available at the library on campus and the author has written other books as well.

[3] Lewis Smith, D.H Sheingold, *Noise and Operational Amplifier Circuits* [Online]. Available: http://notes-application.abcelectronique.com/013/13-14904.pdf

Could help my project by helping me understand noise and the offsets to the voltage levels caused by input biasing.
This source has authority since it has been peer reviewed by three authors meaning that it must have been fact checked and disputed among the authors who are all accredited engineers.

[4] Yael Nemirovsky, Igor Brouk, Claudio G. Jakobson, May 2001, *Noise in CMOS Transistors for Analog Applications*, [Online], Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=918240&queryText%3D1%2Ff+cmos

Could help my project by explaining how noise in analog applications occur and how to mitigate them.
This source has authority since it was written by three authors, meaning that it had more than one person's input on the matter. It was also published in the "IEEE Transaction on Electron Devices" journal.

[5] Hamatasu, Information is current as of January 14th, *Si Photodiodes, S1336 Series*, [Online], Available: http://www.hamamatsu.com/us/en/product/category/3100/4001/4103/S1336-8BQ/index.html

Could help my project by telling me voltage and current characteristics of photo diode under difference in light. This source has authority since it was written up by Hamamatsu and they have been in business for photonics since 1953.

[6] Liu; Kuo-Chi , Tsai; Fu-Sheng ,Chang; Chung-Cheng ,Li; Kuang-Feng ,Lee; Yen-Te, *Power Reduction of a Power Supply Unit at Light Loading or No Loading*, U.S Patent 20120235658 A1, November 12,

2013, [Online], Available: http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&p=1&u=%2Fnetahtml%2Fsearch-bool.html&r=6&f=G&l=50&d=pall&s1=%22363%2F21.09%22.CCLS.&OS=CCL/%22363/21.09%22&RS=CCL/%22363/21.09%22

Could help my project by reducing the power from power supplies connected to the op amp + and – terminal.
The source has authority since it had five inventors and used five different patents as references.

[7] National Semiconductor, *LM118/LM218/LM318 Operational Amplifiers*, August 2000, [Online], Available: http://ee-classes.usc.edu/ee459/library/datasheets/LM118.pdf,

Could help my project by implementing into overall circuit since has 50V/uS, much higher than current circuit comparator (0.5V/uS)
The source has authority since National Semiconductor was founded in 1959 and bought out by Texas Instruments which probably shows that they are an authoritative company.

[8] Herbert Rutgers, *The I/V* Converter, April 2013, [Online], Available: http://www.by-rutgers.nl/IV-converter.html

Could help my project because the author tested IV converters with many different op amps and has plots to show their characteristics.
This source has authority because the author is in Audio Engineering Society.

[9] Author unknown, *BNC* Connector, last modified on January 10,2014, [Online], Available: http://en.wikipedia.org/wiki/BNC_connector

Could help my project by helping me understand the characteristics of BNC connectors.
This source has authority since it has cited eleven different sources and cited Thomas H. Lee ,*Planar microwave engineering: a practical guide to theory, measurement, and circuits, Volume 1* Cambridge University Press, p. 111 (2004), which has been cited 3750 times.

[10] Analog Devices, *Understanding How Voltage Regulators Work*, date unknown, [Online], Available: http://www.analog.com/en/content/ta_fundamentals_of_voltage_regulators/fca.html
Could help my project by teaching me how voltage regulators work if I need one for my circuit.
This source has authority since Analog Devices is the best in High Performance Signal Processing.

[11] Rob Point, *I-V Converter for Polymer Lab*, 1999, [Online], Available: https://courseware.ee.calpoly.edu/~dbraun/polyelec/I-VConverter/IVConverter.html

[12] R. Ford and C. Coulston, *Design for Electrical and Computer Engineers*, McGraw-Hill, 2007, p. 92, 205, 37, 198

[13] *IEEE Std 1233, 1998 Edition*, p. 4 (10/36), DOI: 10.1109/IEEESTD.1998.88826

[14] Linear Technology, *LT1054/LT1054L Switched-Capacitor Voltage Converter with Regulator*, 2014, [Online], Available: http://cds.linear.com/docs/en/datasheet/1054lfg.pdf

[15] Linear Technology, *LT1012A/LT1012 PicoAmp Input Current Microvolt Offsent Low Noise Op Amp*, 2014, [Online], Available: http://cds.linear.com/docs/en/datasheet/1012afbs.pdf

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Appendix B: LTSpice Netlist for Simulation and Monte Carlo Analysis

```
* C:\Program Files (x86)\LTC\LTspiceIV\SeniorProjMC.asc
V§12V_Wallwart V+ 0 PULSE(0 12 0 1m)
C1 N008 N009 {mc(100u,tol4)} tc=2e-06
C2 Cap+ Cap- {mc(100u,tol4)} tc=2e-06
XU1 N003 N004 0 Cap- N008 N006 N005 V+ LT1054
R2 Iin Vout {mc(200k,tol)} tc=50e-6
C4 Iin N002 {mc(100p,tol2)} tc=900e-6
I§Photocurrent 0 P001 PULSE(0 50u 1.5m)
XTIA 0 Iin V+ N007 Vout LT1012
R§ESR N002 Vout {mc(0.225,tol3)} tc=50e-6
R§ESR1 N001 V+ {mc(0.225,tol3)} tc=50e-6
R§ESR2 Cap+ N004 {mc(0.225,tol3)} tc=50e-6
R§ESR3 N009 0 {mc(0.225,tol3)} tc=50e-6
C3 N001 0 {mc(2.2µ,tol2)} tc=900e-6
R1 Iin P001 {mc(1,tol3)} tc=50e-6
Q1 N007 P002 N008 0 2N2222
R3 0 P002 {mc(10k,tol)} tc=50e-6
R4 V+ N007 {mc(100k,tol)} tc=50e-6
C5 N007 0 {mc(10u,tol2)} tc=2e-06
C6 Iin 0 {mc(2p,tol2)} tc=900e-6
.model NPN NPN
.model PNP PNP
.lib C:\Program Files (x86)\LTC\LTspiceIV\lib\cmp\standard.bjt
.param tol=.05 ; +/- 5% component tolerance
.param tol2=.10 ; +/- 10% component tolerance
.step param X 0 200 1 ; a dummy parameter to cycle Monte Carlo
runs
.MEAS TRAN gain PARAM V(Vout)/I(Photocurrent) AT=16ms
* .step temp -25 125 10
.param tol3=.5 ; +/- 50% component tolerance
.param tol4=.25 ; +/- 25% component tolerance
.tran 0 16m 0 16u
.lib LT1054.sub
.lib LTC.lib
.backanno
.end
```