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An Avalanche Transistor-Based Pulse Generator Design For Infrared Laser Applications

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AN AVALANCHE-TRANSISTOR-BASED PULSE GENERATOR DESIGN FOR INFRARED LASER APPLICATIONS

By

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ABSTRACT

This thesis details the design and results of a circuit intended for infrared laser applications, specifically for transcranial infrared light simulation (TILS) experiments and for use as a range finder. The circuit itself is comprised of a transistor, high voltage power supply, laser diode, capacitor, resistor, diode, and low voltage pulse. The design of a range finder is also developed. The range finder design is the same as the circuit developed for TILs with the addition of a few more components for receiving the returned light pulse such as a photodiode, op-amp, and comparator. The techniques used for a successful circuit design are described. For the TILS experiments the design must be able to output a very-high amplitude current pulse in a short amount of time, nanoseconds to picoseconds, to the laser diode. It is shown, and discussed, that the size of the capacitor, the value of the high voltage supply, and the switching characteristics of transistor used, determine the characteristics of the circuit's output pulse. For the second design presented in this thesis, the range finder, the circuit operates by measuring the time difference, using an oscilloscope, between the output of the transmitter circuit and the output of the comparator. The comparator output is a square voltage pulse signifying a received laser pulse from the laser diode once the light reaches the photodiode. Once the time is measured it is used to calculate distance, where it is shown and discussed the range finder's performance from distances of centimeters to meters.

ACKNOWLEDGEMENTS

In the pursuit of my master's degree here at UNLV, I have met extraordinary people who have made a great impact on how I think, what I was able to accomplish, and what opportunities I had available to me. The first of those people is Dr. Baker, who gave me the opportunity to work in his lab and contribute to research that eventually led to the thesis I'm writing now. Everything that I learned and take pride in from UNLV comes directly from Dr. Baker's courses and that has helped not only decide what I want to do as a career, but it has also opened the door for a path in higher education that I would have never thought possible when I first started, so as I'm sure he's read and heard many times; thank you for everything.

Next, I would like to thank my committee members for not only accepting to be in my committee, but also for their individual impacts throughout my education. Dr. Baghzouz and Dr. Das both of you have made a significant contribution to my education from Dr. Baghzouz's classes in power system engineering and Dr. Das with the special topic classes he's taught, but also as the department chair helping with approval of forms and petitions. Also, thank you to Dr. Li for being a great professor when I was taking Math 432, which helped greatly with signal processing.

Another group of people I would like to thank is Dr. Hines and his research group, particularly Haley Strong and Kendra McGlothen. If not for Dr. Hines, there wouldn't have been a circuit to build as he was the one who approached Dr. Baker with the idea for the research and luckily for me, I was assigned to help. Haley and Kendra were great as they helped with the experiments, were always helpful explaining certain concepts to me to build what they needed, and they helped with the research paper that was published on TILS.

Lastly, a big thank you to everyone from the Baker research group. Firstly, I would like to thank Daniel Senda who was the first person I met in the group and acted as my mentor/guide by teaching about his research, how things worked in the lab, by introducing me to everyone else in the lab and always being there if I needed help or had questions. Francisco Mata was someone who always gave me good advice, made me think from a different perspective, and helped me get my first job as an electrical engineer. Another person who was helpful was James Skelly, not only as a TA, but also as someone who was able to help with any homework problem I was stuck with. Someone who always encouraged me and told me I could do great things was David Santiago. Lastly, Armani Alvarez who has always just been a great friend to me and a good person to work with since EE 220, has been nearly 4 years since then.

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CHAPTER 1 – INTRODUCTION

Transcranial infrared light stimulation (TILS) is a method of stimulating neurons in the brain. Stimulating neurons in the brain can be a form of therapy for people with mental disorders, however there is a current movement in the field of neuroscience that believes that TILS can be a solution to treat mental disorders such as PTSD, depression, anxiety disorders, and more.

To perform neuron stimulation with TILS on a subject, an infrared laser with the wavelength range between 780 nm to 1 mm is used. The laser needs to be in this spectrum of near-visible to infrared light to have the most effect on the neurons of the brain. Specifically, the infrared light from the laser introduces a temperature gradient to the neurons that when exposed open electrical pathways in the brain. The characteristics that determine how greatly the neurons respond to this come from the specific wavelength of light hitting the neurons and how long the neurons are exposed to the light. Being able to control these characteristics is what determines the success of TILS experiments, hence particular circuitry is needed to generate the current needed to power on the laser diode with a wavelength of 780 nm and for a specific period or pulse of around 2 ns, which is ideal for impulse response excitation.

A circuit for TILS experiments is comprised of a high input voltage source, capacitor, resistor, transistor, and laser diode. It may seem that the circuit is simple, but each of those parts are responsible for a different parameter in the circuit's design, hence the following chapter will delve into what is necessary to build a circuit that can be used in TILS experiments that involve small animals and is compact to have a small weight. Also, it should be noted that this idea for designing a circuit for TILS research was from Dr. Hines, who specializes in neuroscience and is a professor here at UNLV in the psychology department. Hence, some parts of this thesis will detail some of the work they did as his research group was responsible for the neuroscience research, while the author and Dr. Baker designed, built, and tested the circuit they used for their experiments.

Laser diodes can be used for more than just the TILS experiments as they have many applications in other common devices such as printers, scanners, and security systems. One application is as a tool to measure distance or more commonly referred to as a range finder. The premise of a range finder is simple; a laser is aimed at a distant object then once the laser hits the object it will reflect to the rangefinder. The rangefinder then calculates the distance of the object, by taking the time it took the laser to reflect to itself by using a high-speed clock. The circuit design in this thesis attempts to accomplish the same concept as the circuit can already pulse a laser which beams at an object. All that remains is taking the reflection of the laser beam and using that to calculate the distance of the object, which is accomplished by using a photodiode; detailed in the following chapters later.

Note that the application of using the pulse generator design for a range finder has no relation to the TILS experiments. As the author wished to show that the design with a few modifications can be used for more than just a particular area of TILS research.

CHAPTER 2 – AVALANCHE TRANSISTOR BASED CIRCUIT FOR TILS

An avalanche-transistor-based pulse generator is essentially a circuit that can output a current or voltage pulse with a fast edge, meaning that the rise and fall time of the output pulse is less than or near a nanosecond. What allows the pulse generator to accomplish this is the transistor, also known as a BJT, operating in current mode second breakdown, which will be referred to in the rest of this paper as an avalanche transistor. To help illustrate what avalanche is in terms of a transistor, Figure 1 shows the I-V characteristics of a p-n junction or diode as more commonly known.

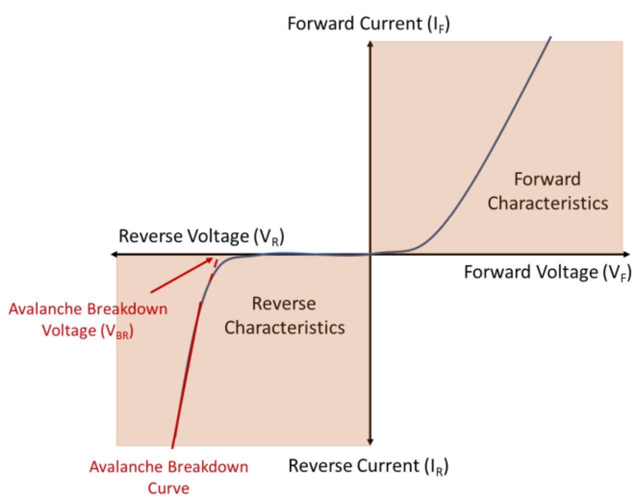
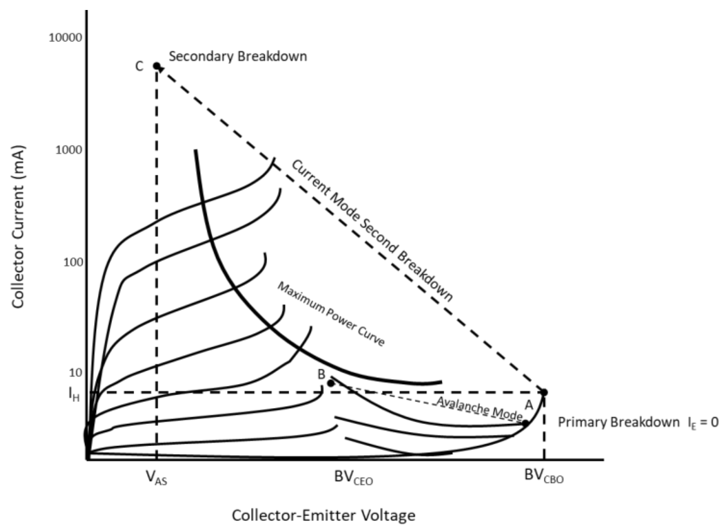


Figure 1 – IV characteristics of a diode

Notice in Figure 1 how the diode has specific point at which the reverse voltage becomes large enough to be the breakdown avalanche voltage, where the reverse current through the diode quickly increases in a short amount of time and usually damages the diode. The same kind of premise applies to the avalanche transistor as a large voltage is applied to the collector of the transistor to force a breakdown that causes a large amount of current to flow through but operating in that region can severely damage or destroy the transistor unless operated in a more stable mode or in a short time frame.



[2]

Figure 2 – IV characteristics of BJT

This is evident in the I-V characteristics of the BJT seen in Figure 2, where point A' to point C represents the load line or operating region of current mode second breakdown. As the collector-emitter voltage passes the breakdown voltage, collector-emitter, base open (BV_{CEO}) and reaches the breakdown voltage, collector-base, emitter open (BV_{CBO}). The transistor near the maximum power curve can output a collector current from 100 mA to about 10 A, which occurs when switching hundreds of volts, hence the need to find a stable state for operating the avalanche transistor by limiting the time it operates in second mode current breakdown. Before continuing with the actual TILS circuit design, it is important to stress the fact that the pulse generator is manually triggered or set via an input voltage pulse. The reason is, because the avalanche transistor will self-reverse bias itself due to the high voltage on the collector of the BJT at a frequency that depends on the values of the capacitor and resistor on the collector. For example, in Figure 3 is an avalanche pulse generator that doesn't have a manual trigger on the base pin of the BJT, notice that the base is connected to ground through a 10k resistor.

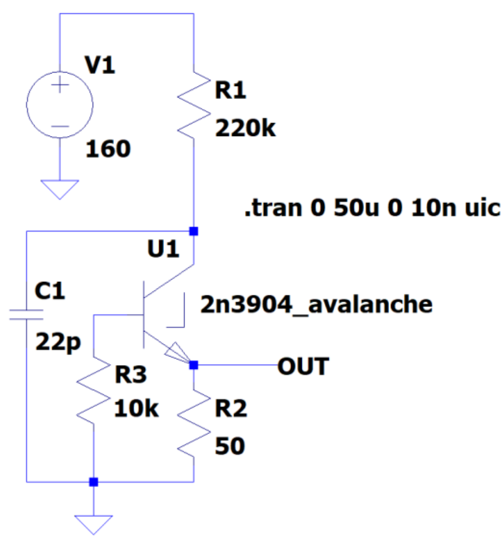


Figure 3 – Avalanche pulse generator without trigger

Instead, the pulse generator will trigger once the capacitor C1 is charged and the time it takes to charge is based on the values of C1 and R1, which is 22 pF and 220 kΩ. That is a RC time constant of 4.84 µs or a frequency of 207 kHz at which the circuit will output a pulse. Once the capacitor is discharged the current breakdown stops until the capacitor charges again, where the process repeats. Figure 4 verifies this output by showing the collector current and voltage output of the pulse generator occurring every 4.84 µs, while Figure 5 shows the capacitor charging and discharging relative to the output.

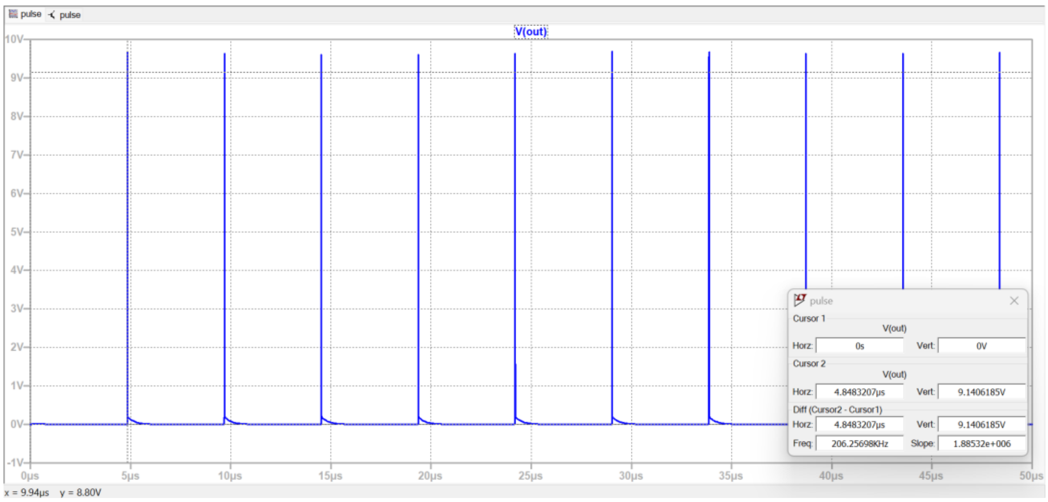


Figure 4 – Output of the avalanche pulse generator

A few things to note about this design, one is the purpose of R2 and R3. R2 is meant to simulate the resistance of a 50 ohm termination that would be connected to an oscilloscope. The original function of an avalanche pulse generator was to test the effectiveness of oscilloscope probes by providing a fast-edge pulse to measure. Now the purpose of R3 is to bias the base of the BJT so that it goes into current breakdown, and the resistance must be relatively high with the value being around 10 kΩ to deal with the reverse current from the collector. Lastly, the capacitor C1 will determine the magnitude of the output pulse and for this circuit the operating frequency, but if the capacitor value is too large than the capacitor’s charge can shoot through the BJT meaning it will destroy it, see the simulation in Figure 6.

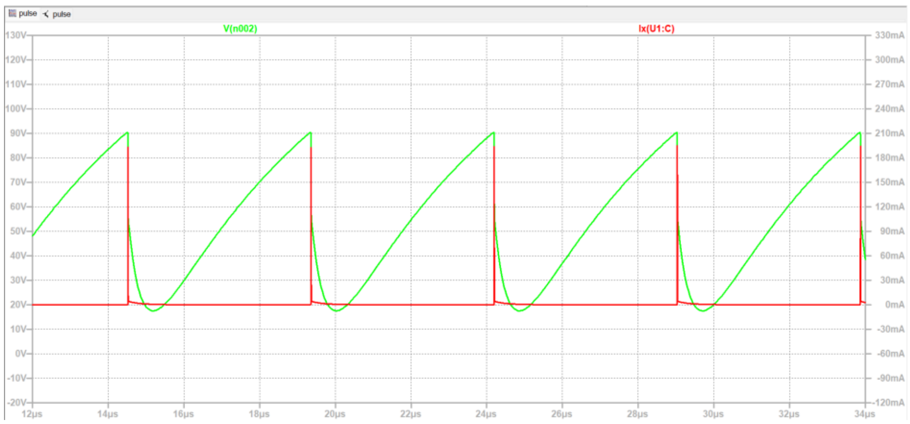


Figure 5 – Capacitor C1 charging and discharging relative to the output pulse

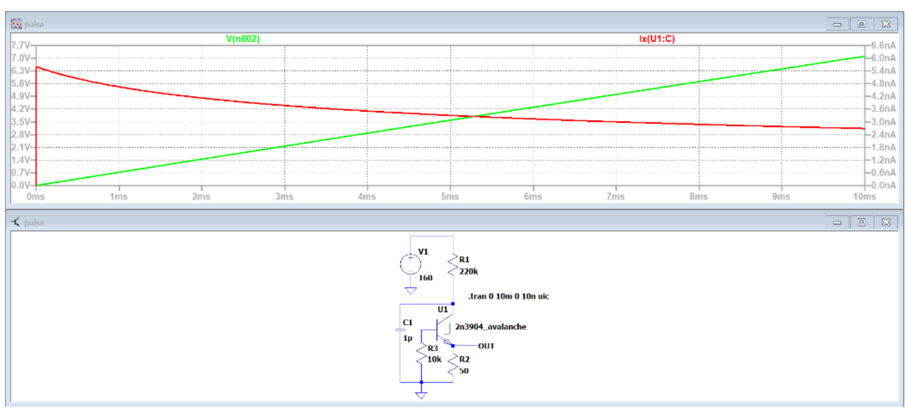


Figure 6 – Simulation of Avalanche pulse generator with large capacitor

Moving on to the avalanche pulse generator design for TILS seen in Figure 7, where there are several new additions to the avalanche circuit that was shown earlier. One of the new additions that is important for TILS experiments is the manual trigger, as stated earlier, via a 1N4148 general purpose diode and a voltage pulse of 1.6 V with a period of 10 µs. The reason the manual trigger is such an important part of this design is that it gives the user control over when the transistor is biased, which means control over when to output a pulse or turn on the laser diode. Also, consider that this device in being used on a mouse's or other small animal's brain, so if the design was the previous pulse generator that sent out repeated pulses at some interval with no way to control it, then it could end up putting the mouse or other small animal at harm.

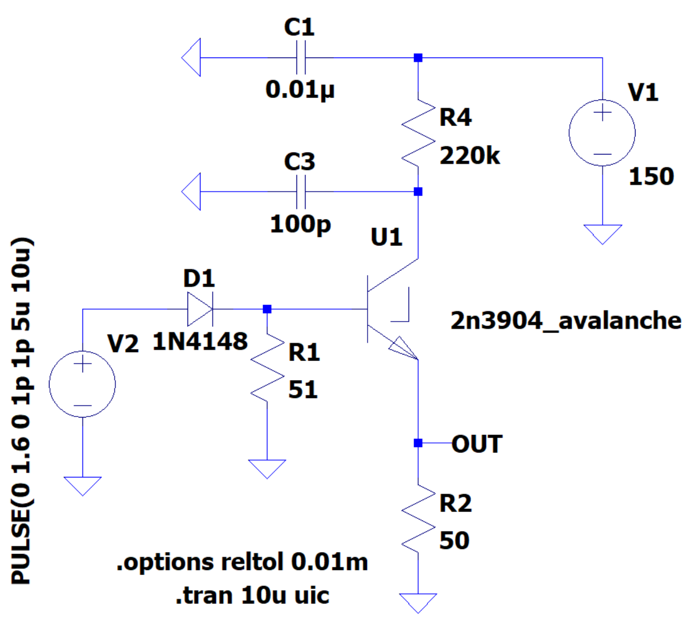


Figure 7 – Avalanche pulse generator for TILS experiments

The reason a manual trigger is achieved with a diode and the voltage pulse on the base of the BJT is because the diode prevents the reverse bias of the BJT from the high voltage on the collector charging the capacitor C3. As the general purpose diode needs to be forward-biased by the voltage pulse to bias the BJT as well; there is still a reverse current coming through the collector, but since the resistance R1 on the base pin is low at 51 ohms it's not enough to self-bias the BJT by turning on the base-emitter junction as it decreases the hold off current (I_H), more on I_H later. The other new addition to the pulse generator is the 0.01 µF capacitor C1 and the purpose for it has no direct influence on the pulse generator itself, rather it is there for decoupling the high voltage from the power supply or in other words it keeps the voltage stable.

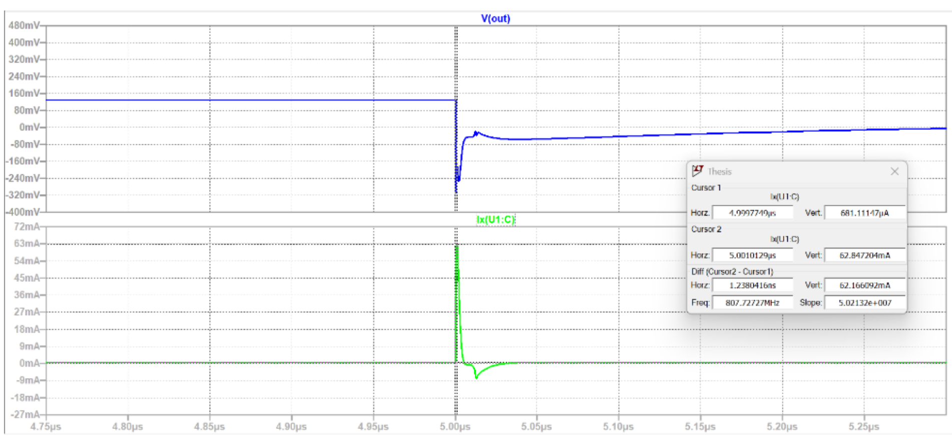


Figure 8 – Output pulse of TILS pulse generator

The role of resistor R4 has changed as well, where with capacitor C3 it dictated the operating frequency of the output pulse, it now affects the I_H instead, where its large value ensures that any fluctuations in the breakdown voltage only has a small effect on the collector current. Now, the hold off current is the maximum collector current that can be put in the collector pin of the BJT, when the collector-emitter voltage is approximately equal to BV_{CBO} and is in this specific circuit configuration. Hence, the collector current should be lower than the I_H while still maintaining the avalanche transistor in breakdown mode, see Figure 2. Then, as the input voltage pulse forward-biases the base-emitter junction, it causes the collector current to pass the I_H causing the transistor to go into second breakdown. Also, note that not every BJT can be used as an avalanche transistor, only BJTs with a high collector terminal resistance, such as the 2N3904 with 100 mΩ, function well as avalanche transistors. If the BJT does not have a high collector resistance, then the voltage potential across the collector and base region can extend to the emitter. This does not allow the collector-base junction to go into avalanche breakdown and this type of phenomena is known as punch-through, hence BJTs that have this cannot be used as avalanche transistors.

Finally, looking at Figure 8 to see of the output results of the TILS design, notice the rising edge of both the voltage output and collector current of the pulse generator is 1 ns, the speed needed to pulse the laser diode functionally correct for TILS experiments. The peak output amplitudes for the current and voltage, which are 63 mA and -300 mV respectively, are suitable to meet the maximum threshold and operating currents of the laser diode being 50 mA and 60 mA. This allows for the maximum optical output of 4.5 mW that the laser can output. There is one more aspect of the design to address and that is the amplitude of the voltage pulse. When the TILS circuit was first built there was no design through simulation, instead it was built first to see if it could work right away as the circuit was simple. At that time the author was not aware of the proper forward-bias voltage pulse for the TILS circuit, so in the first tests of the actual built device a voltage pulse of 5 V was used instead of 1.3 V as it was an input used for a similar experiment in a TMS (transcranial magnetic stimulation) circuit design. The simulation results in Figure 9, show the collector current and output voltage when using a 5 V pulse.

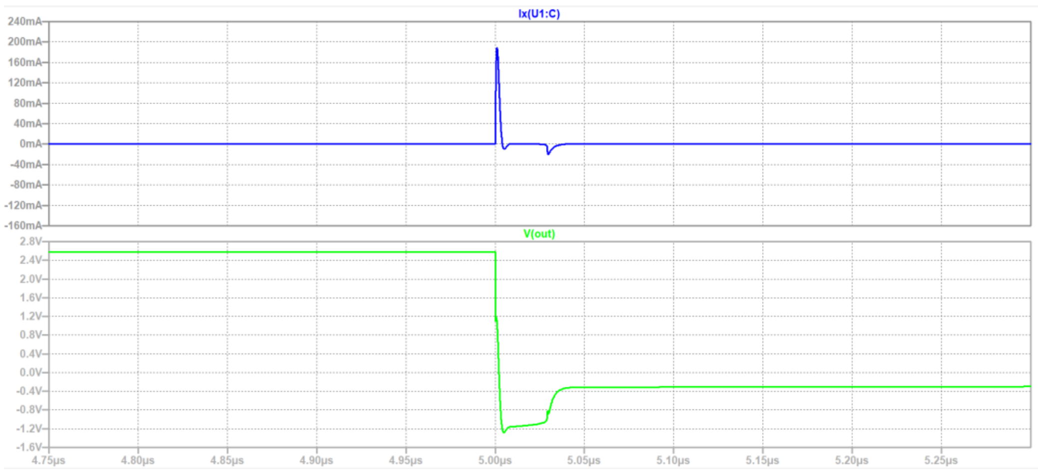


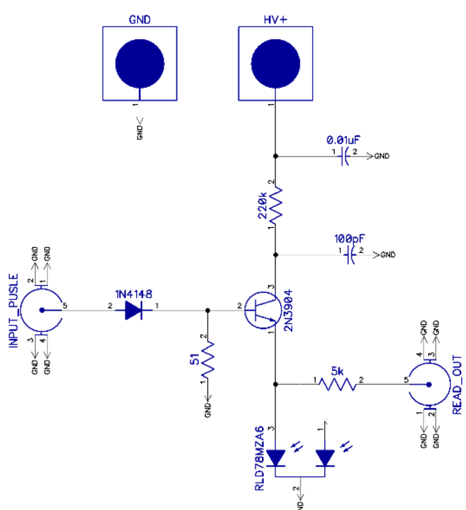
Figure 9 – Output of TILS circuit with 5V pulse

Notice that the main difference between the outputs shown in Figure 8 and 9 is the peak amplitudes of the collector current and voltage output of the pulse generator, but more importantly the rise time is still 1 ns. The reasoning being that the increase in amplitude in the voltage pulse only affects the amount of collector current passing through the transistor. As mentioned before, when the pulse forward-biases the transistor causing the collector current to go beyond I_H the transistor goes into second breakdown albeit at a now higher current. Also, the larger pulse causes the output voltage to saturate for a constant voltage, here around -400 mV, until the pulse goes back down to zero. This is all to say that these outputs will not change the optical output of the laser diode, which will be seen in chapters 3 and 4.

CHAPTER 3 – BUILDING AND TESTING TILS CIRCUIT

Now that the simulated design is completed, the next step involves creating the printed circuit board (PCB) that will house all the components into a compact device. Before designing the PCB schematic, it's important to know what electrical components the design will use by selecting them based on certain characteristics and their availability on Digi-key. The first component to pick is the laser diode, which for this design is the RLD78MZA6. This component is a 780 nm invisible multi-mode laser diode module that has an infrared laser diode and a photodiode rated for the same wavelength; the RLD78MZA6 schematic can be seen in Figure 10 to understand its connection in the design. The module itself is a three pin lead component with a shared ground and pins for the laser and photodiode terminals. The next part is the 2N3904 transistor that has a TO-92 package model, which means it's a through-hole part with three pins for the base, collector, and emitter. It was selected not only because it could be used as an avalanche transistor, but also because the component is available in surplus. Then the next parts are two banana jacks that will serve as the input connections for ground (GND) and high voltage (HV) for the high voltage generator that is connected to the board with banana jack cables; again, all schematics for the parts can be seen in Figure 10.

Next is addressing how to send an input voltage pulse to the board via a function generator, also how to read the output of the circuit from an oscilloscope and the parts used to achieve these requirements was two Sub-Miniature version A (SMA) connectors connecting to the function generator and oscilloscope with coaxial cables. Note that for oscilloscope there is also a 50 ohm termination which for the circuit acts as a 50 ohm resistor. Also, note that there is a slight difference here for this schematic compared to the design schematic with a 5k resistor connected to the emitter of the transistor and the SMA going toward the oscilloscope. The reason for this change is to create a 100:1 voltage divider with the 5k resistor and 50 ohm termination (acts as a resistor) to see the output voltage magnitude on the oscilloscope, hence this change is purely for observability of the output voltage and will not impact the original performance of the TILS circuit. It was covered in the previous chapter the purposes of all the resistors and capacitors in this circuit, but for their physical representations on the PCB, there are several important characteristics for these specific parts that must be followed. These characteristics are the voltage rating of the capacitors, the metric size of the capacitors, the safety rating of the resistors, and power rating of resistors. The voltage rating for the capacitors is 200 volts while the input voltage is 150 volts, so the capacitors can withstand the physical pressure from the voltage. To make the board compact, the capacitors need to be relatively small, hence the reason these capacitors are surface mount devices (SMDs) with metric sizes of 0402 (40 x 20 mils) and 0603 (60 x 30 mils). For the resistors to withstand high voltages their power rating must be adequately high enough to withstand those higher voltages even if there is little power being dissipated by the resistors, hence the reason the resistors are power rated for 1/4 W.



[1]

Figure 10 – PCB Schematic of TILS Circuit

It’s important to state that for the resistors to have a higher power rating the type of resistor must be an axial lead type, but since the power rating 1/4 W an SMD type can be used for the resistor on the base terminal. The resistors above the collector and below the emitter must be an axial lead type to have a specific safety feature of being flame proof or flame retardant in case the input voltage exceeds the power rating, preventing the resistors from catching on fire. The only part left is the diode for the manual trigger of the circuit, which is the 1N4148 diode picked for being a common general purpose diode that is easy to acquire, and its package type is an axial lead for through hole mounting.

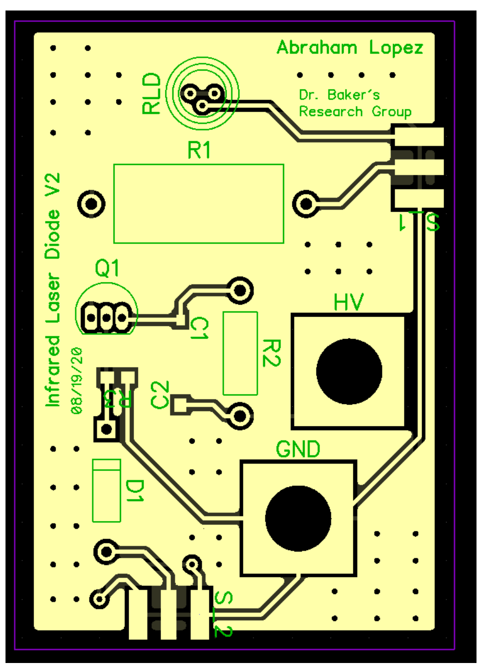


Figure 11 – Front PCB layout of TILS circuit

Now that all the parts are selected, along with knowing their respective packaging types and sizes, then the PCB design can be started by first making the schematic in a PCB design program called DipTrace. DipTrace has multiple modes that include schematic capture, PCB layout, and component design. Each of these design modes were used on the making of this PCB starting with the schematic capture.

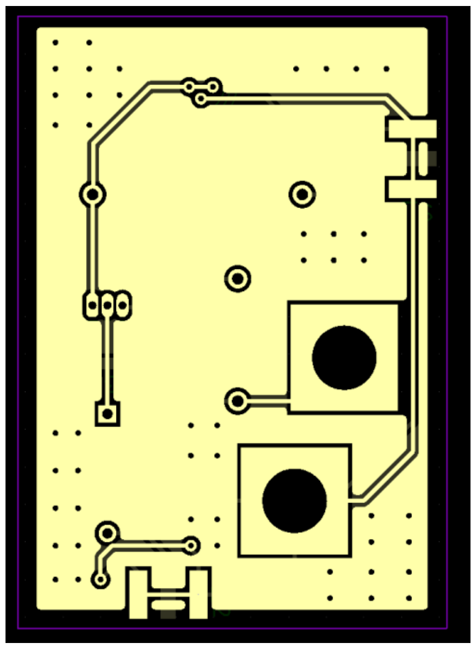


Figure 12 – Back PCB layout of TILS circuit

The schematic capture is simply a program that lets a user draw the circuit that needs to be built as can be seen in Figure 10, which shows the schematic capture program with the TILS circuit that was designed in chapter 2, note how similar it looks to the schematic from LTspice. Much like LTspice, the user places components that are available via built-in libraries and connects them using a wire draw function. These libraries not only allow for the placing of component symbols, but they also have the attached patterns/footprints and terminal definitions for the components. These patterns allow for the schematic to be exported to a PCB layout in DipTrace and many other PCB design programs. It is then imperative that each component in the schematic capture have an attached pattern with the correct terminal pins assigned to it.

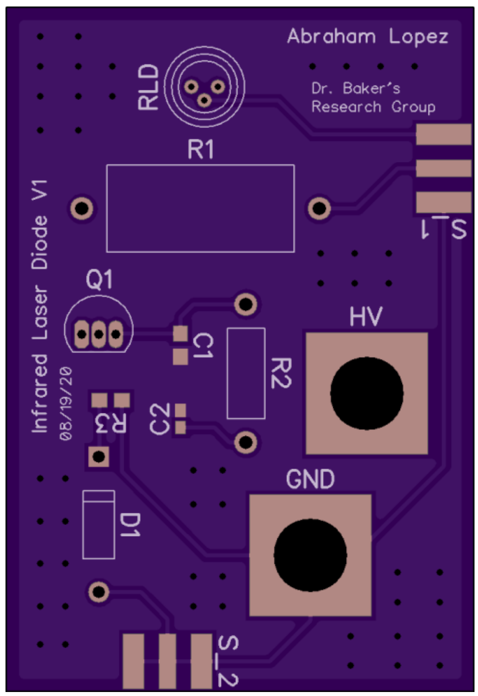


Figure 13 – Rendered front of PCB for TILS circuit

This is where the component design mode comes in, as parts like the RLD78MZA6, SMAs, and banana jacks are not in the built-in libraries for DipTrace nor are there libraries that can be download that have the schematic symbols, terminal definitions, and patterns. The only option then is for a user to make the symbol, the pattern, and define the terminals by using the components datasheet. As the datasheets contain the metric sizes of the components to use in creating the patterns and the terminal definitions that show where each pin should be connected to.

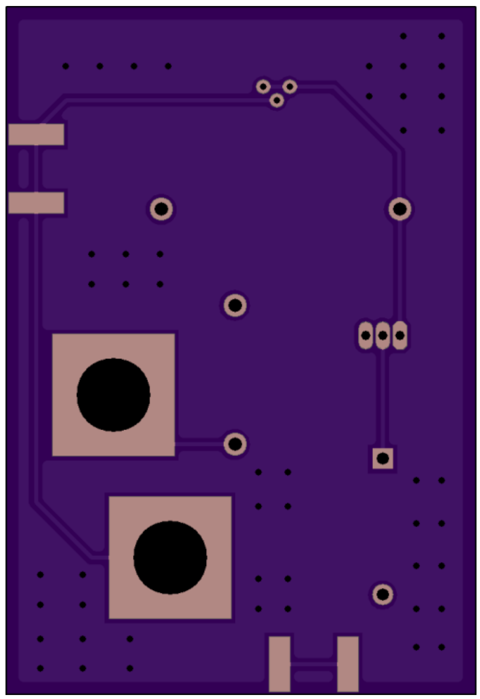


Figure 14 – Rendered back of PCB for TILS circuit

With the custom components made and the schematic finished, the next step is to export the schematic into the PCB layout program. Once exported, the component's patterns will appear scattered about with blue lines (rat lines) showing what pins or through holes need to relate to a trace (copper line through the circuit board). The components are placed in their respective positions, for example the SMAs are placed on the edge of the board, by being as close as possible to make the board compact, but with enough room that the components are not touching. Then the components are connected as they were in the schematic with traces running from one footprint to the other. After that, a board outline is placed around the components that define the size of the PCB. That outline is then filled in with a copper plane that is connected to ground and the result is seen in Figures 11 and 12, with the completed PCB layouts for the front and back of the board.

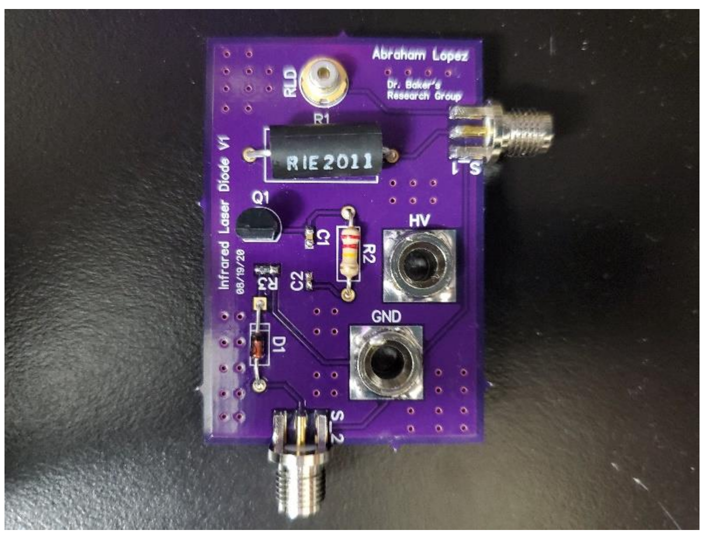


Figure 15 – Completed front of PCB for TILS circuit

A couple of items to note about the PCB layout design, the first is that this PCB is only two layers, and both have a filled copper background that is connected to ground to reduce any noise or avoid electrical interference. The other is the groups of vias spread around the PCB and the reason for these groups of vias is to also reduce noise, avoid ground loops and to make connections between PCB layers. Now that the PCB design is finished the PCB file is exported as a Gerber file with the drill hole locations, so it be fabricated at a PCB manufacturing company. The company used for the manufacturing of this PCB design is OSH Park, known for their 2 layer PCB prototype service and lead free boards, and provide a free service that takes the PCB Gerber file then renders it. Giving the customer an idea of the finished product will look with the silkscreen and solder mask layer, which can be seen in Figures 13 and 14.

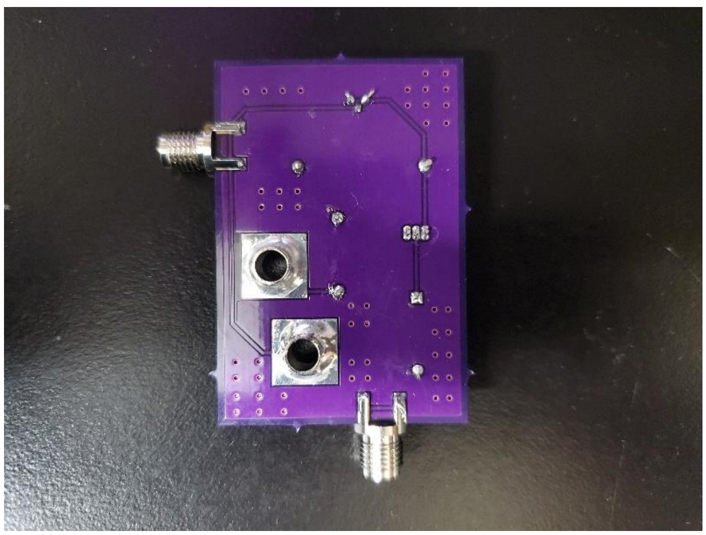


Figure 16 – Completed back of PCB for TILS circuit

Now that the PCB is fabricated, the components from before are soldered onto the front and back of the PCB, which is shown in Figures 15 and 16. A couple of observations to consider when looking at Figure 15 is that the laser diode is directly soldered onto the board. The first reason the laser is on the board here is, at the time of building, the author wasn't aware of how the method used to connect laser diode to the small animal test subject. Only when given feedback from Dr. Hines's group, as they were worried about the weight of the board being too much if placed directly onto the small animal's head, was the placement of the laser moved to a more convenient location for testing, covered later in chapter 4. The second reason was to see if the design worked with laser directly on it and to see if there were any problems with the first iteration of the PCB. Unfortunately, there were two major problems with the PCB design that made testing the design futile. One problem was with the trace connections for the SMAs, for reference see Figure 15 with the components label S_1 and S_2, as those traces were shorted together to ground due to an error made in the PCB layout program. The other error was that the laser diode and photodiode pins of the module were shorted together on the PCB design, effectively shunting (diverting) the current from the laser diode, greatly reducing its performance.

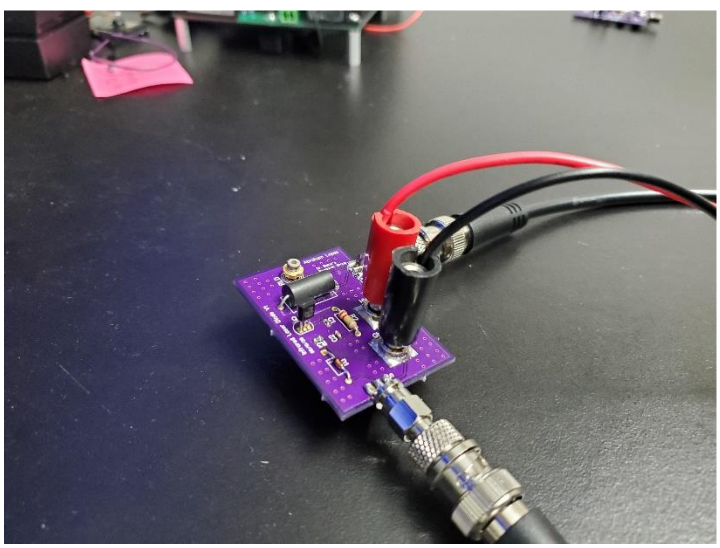


Figure 17 – Testing set up of the TILS circuit

Fortunately, fixing the trace errors is simple and doesn't require ordering a new PCB with changes, at least not yet. Instead, the traces that are causing the shorts can be ripped out without affecting other components on the PCB with a utility knife or other kind of sharp tool. Now that those issues are dealt with, the TILS circuit can now be tested with the configuration seen in Figure 17. Where the PCB is connected to the high voltage generator with a red and black banana jack. Also, there are two coaxial cables connecting to the SMAs with one of each connecting to a function generator for the input pulse and the other connecting to an oscilloscope to the voltage output which can be seen in Figure 18. Note that the settings for the function generator is a 5 V pulse with a period of 10 µs (50 percent duty cycle) and the high voltage generator is set to 150 V. Here the oscilloscope is measuring the voltage output from the emitter of the avalanche transistor and notice the large voltage spike and its close resemblance to the simulated output that was shown in Figure 8.

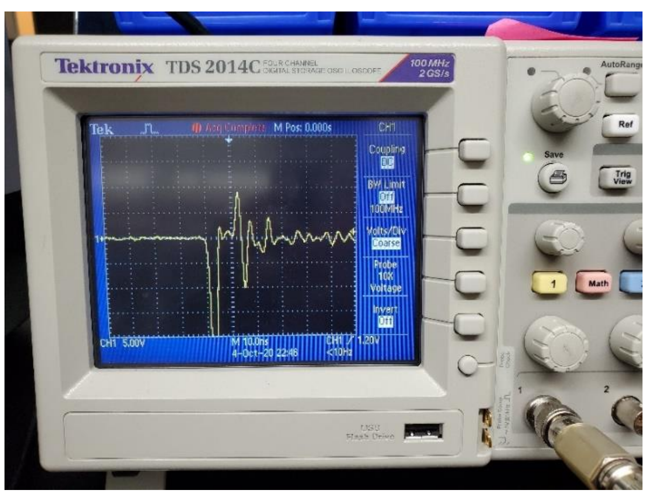


Figure 18 – Voltage output of first TILS circuit test

Also, recall that the rise time of these pulses is very fast at 1 ns and looking at the time window of the oscilloscope at the bottom it displays 10 ns. This observation is important as it verifies the fast edge pulse that was demonstrated early in the simulations for the design, but there are a couple of differences here than those from the simulations. The first most notably being the amplitude of the voltage as it is shown here being much larger than it was in the simulation and the reason for that is because of the 100:1 voltage divider with the 5k resistor and 50 ohm termination that was mentioned earlier. Also, the probe is set to 10X voltage which means the voltage being displayed on the oscilloscope is multiplied by a magnitude of 10.

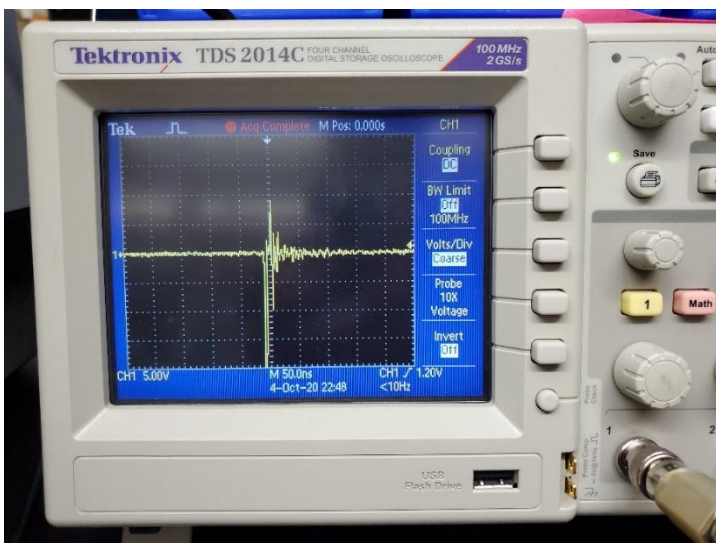


Figure 19 – Noise in the output of the circuit

The other noticeable difference is the other smaller voltage spikes going both up in down until it settles out. The smaller spikes are called voltage noise and their appearance in the output of the circuit is due to random electrical signals coupling into the circuit from parasitic components on the PCB or from the PCB itself. However, the amplitude of our pulse is much larger than the noise therefore the noise will not impact the performance of the TILS circuit, also while the noise may appear large recall the previous statement about the voltage divider and probe magnifying the voltage on the output to make it easier to see, meaning that the noise is quite small.

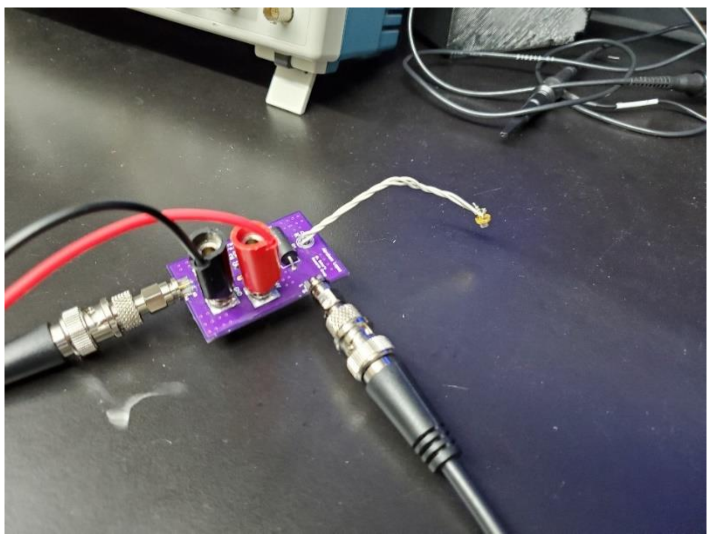
 [1]

Figure 20 – Twisted wire pair connecting to RLD78M

There is one more part to address about this design and that is the connection to the laser diode with it off the PCB, as was mentioned before Dr. Hines's research group did not want the board on the small animal's head. Rather, it was preferred that the PCB was as far as possible from the animal, so the first idea was to use a twisted wire pair soldered to the laser diode off the board, as seen in Figure 20. This solved the issue of potential harming the animal by placing as little weight as possible on its head and it keep the PCB far from the animal as the twisted wire pair was a little more than a foot long preventing the animal from being electrocuted from touching the PCB or equipment. However, the addition of the twisted wire pair introduced an issue by adding a source of parasitic inductance, even with the wires twisted to reduce the parasitic inductance, which will add more noise voltage to the voltage output of the TILS circuit as shown in Figure 21. Notice the increased amplitude of the smaller voltage spikes from earlier and that they're almost as large as the first pulse.

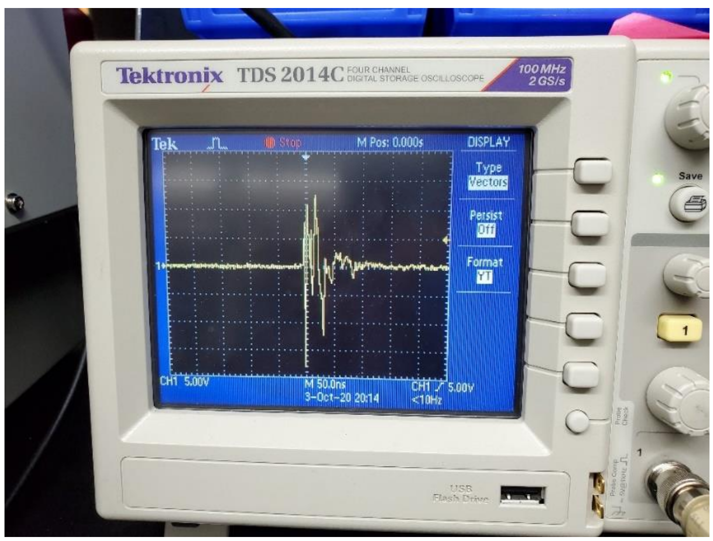


Figure 21 – Voltage output with tested wire pair connected to PCB

To deal with the increased amount of noise, the type of wire used for the connection from the PCB to the laser diode was changed from stranded wire to a single core wire. The single core wire also had a much smaller diameter at 0.5 millimeters which effectively reduces the area of the parasitic inductance resulting in smaller noise voltages. With this change, it resolved the last major issue for the TILS PCB and made it ready for the TILS experiments that Dr. Hines's research group had prepared it to be used for. Also, as a bonus the twisted wire pair became much lighter and looser than before, which helped Dr. Hines's research group in easily attaching the PCB to the laser diode on the small animal and made it possible to make the twisted wire pair much longer and not as tight for a reason that will be covered in the next chapter when the TILS circuit was actual used in experiments.

CHAPTER 4 – HANDS-ON TESTING AND RESULT SUMMARY

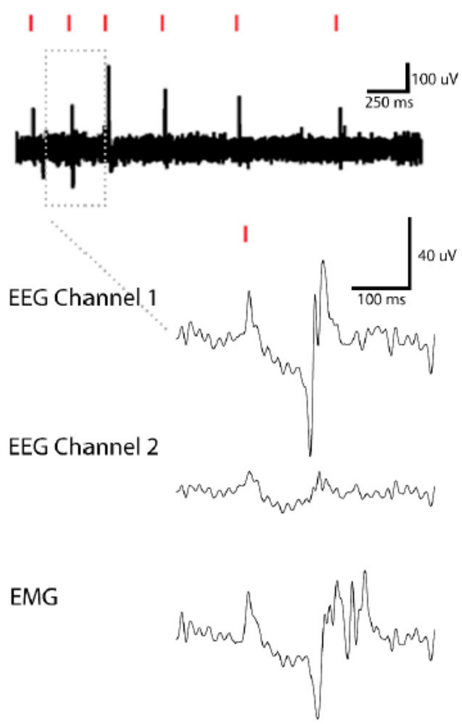
Recall from earlier that Dr. Hines's research group wanted the PCB for the TILS circuit to be away from the small animal, a mouse, and to connect to the laser diode off the board. The purpose behind this can be seen below in Figure 22, where the laser diode is surgically implanted by Dr. Hines's group into the mouse's head and sealed with bone cement. This allows the infrared light from the laser to hit the mouse's brain directly to gain the most effect. Hence, the board needs to connect with the twisted wire pair to the leads of the laser module, which for the first run of the experiment was sticking out until changed later due to difficulties encountered in the first test. Due to the mouse moving its head while being held to connect the wire pair with a female connecter resulting in the first test failing.


[1]

Figure 22 – Mouse being implanted with laser module

Also, the mouse was kept in a clear cylindrical polymer holding where it could move freely during the test, hence it was helpful that the length of the twisted wire pair was increased to reach the mouse and that it's looser to not restrict its head movement preventing injury.

Now to solve the issue for connecting to laser module, the approach changed to soldering a male to female connector to the laser module leads then implanting it into a new mouse. With the female side outside of the mouse's head it's now easier to connect to the laser module with a male connecter soldered to the twisted wire pair.



[1]

Figure 23 – EEG and EMG results from TILS experiments

There was also other electrical equipment implanted and attached to the mouse’s head to observe the electrical activity in the nerves of the mouse. With electrical components capable of sending information to an electromyography (EMG) and electroencephalographic (EEG) machine then plotting those results as seen in Figure 23. Notice the red marks on the plots, these indicate when the TILS circuit was pulsed and the resulting change in brain activity indicated by the spikes in activity. EEG channel 1 and the EMG offer a closer look at the brain activity and changes caused by the TILS circuit where at a 100 ms window after the circuit had pulsed there was a large change in voltage on a 40 μv scale on the brain activity of the mouse before returning to normal. Also, observing the mouse’s physical behavior during the experiment also showed how the circuit was affecting it as when the board was pulsed the mouse would stop moving and freeze up for a few moments before moving again. All the results and observations indicated a successful experiment and showed that the TILS circuit could affect the brain activity of a small animal.

CHAPTER 5 – RANGE FINDER CIRCUIT DESIGN

Transitioning the avalanche transistor-based pulse generator to a range finder involves changing the way current is supplied to the laser module and adding several new components. The current is now being constantly supplied to the laser diode and the photodiode, mentioned earlier, takes a more prominent role in the design. As the infrared light comes from the laser diode it will reflect to the photodiode once it hits an object at some distance denoted by the amount of current flowing through the photodiode. Then by adding additional circuitry in the form of a transimpedance amplifier and comparator to output a pulse that can be used to measure distance based on its frequency.

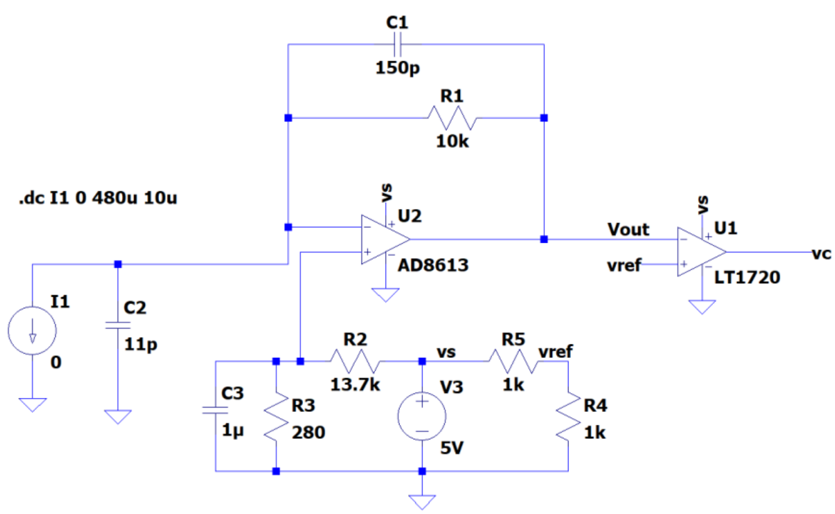


Figure 24 – Range finder circuit design

The basic premise for the design of the range finder circuit is to take the current from the photodiode and amplify it with the gain of the amplifier to get a voltage Vout, seen in Figure 24. The gain determined by the value of the resistor R1 (10k) set by Vout minus the input voltage on the positive terminal of the op-amp divided by the maximum current from the photodiode. The voltage on the positive terminal of the op-amp is 100 mV by using the voltage divider of R2 and R3 on a 5 volt supply. The reason the positive terminal needs to be at 100 mV is to avoid the op-amp outputting a negative voltage, while the capacitor C3 (1 µF) is to put a cutoff frequency to filter the voltage. Also, the capacitor C1 is in this design to avoid stability problems by moving the single pole in the frequency domain of the circuit further down to 100 kHz shown in Figure 25, which is why the value is 150 pF.

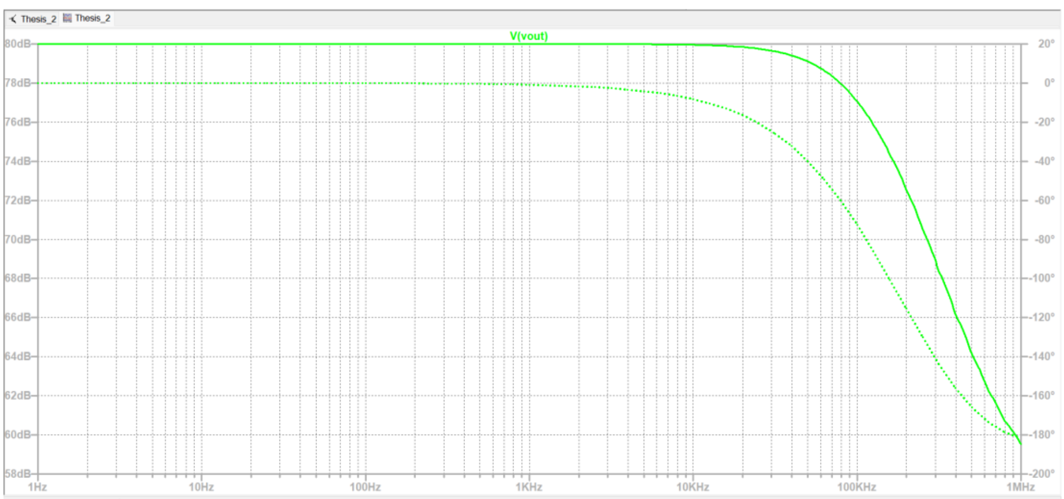


Figure 25 – AC analysis of the range finder circuit

After the amplifier, its output is sent to a comparator to determine if the voltage from the amplifier is past a certain voltage, which is 2.5 volts in this scenario. Note that this 2.5 volt reference (Vref) is from the voltage divider of R5 and R4. Once Vout is past Vref, the comparator will drop from high (5V) to low

(0V) indicating that the photodiode is outputting the desired current which corresponds to the distance an object is reflecting the light from the laser diode, see Figure 26. With this output from the comparator and the input from the photodiode, it's possible to take the difference in time between the two and find the distance of an object that will by multiplying that time with the speed of light constant then dividing it by 2. Lastly as a final note, in Figure 24 notice that to model the behavior of the photodiode input to the amplifier is a current source and a capacitor C2 (11 pF), where the photodiode is treated as current source and C2 is the junction capacitance.

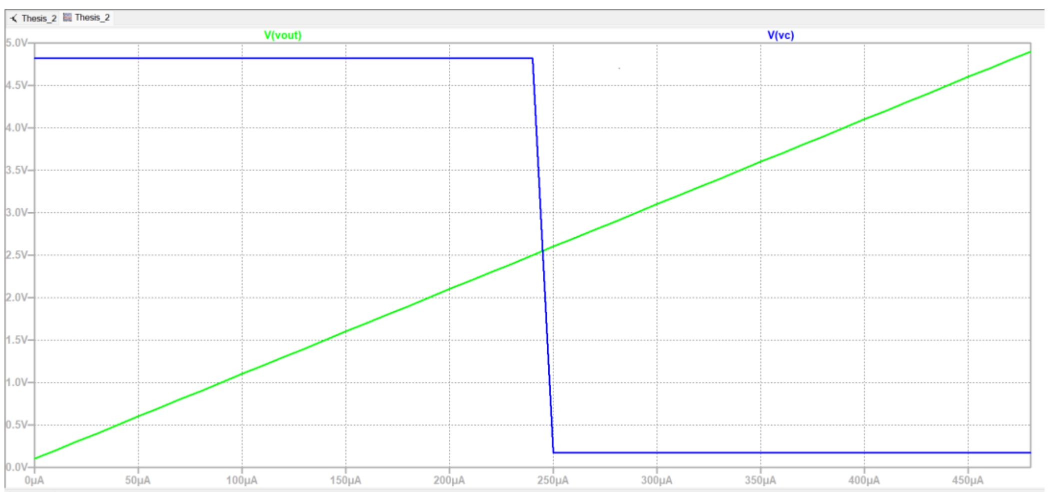


Figure 26 – Output of ampilifer and compartor

CHAPTER 6 – RANGE FINDER BUILD AND TEST

The first step in building the range finder design is to test the range of the laser module, seen in Figure 27. Where the laser diode is being supplied with a constant supply of current, around 40 mA, from the Keithley source meter. There is another source meter used to measure the monitor current coming from the photodiode and show the change in current in a plot form as the distance between a white piece of paper and the module increases and decreases. As the light from the laser reflects from the paper back to the photodiode and the intensity of the light increases as the module comes closer to itself which in turn increases the current in the photodiode or decreases as it moves away. Creating a basic range finder that uses the current from the photodiode to measure distances of several millimeters.

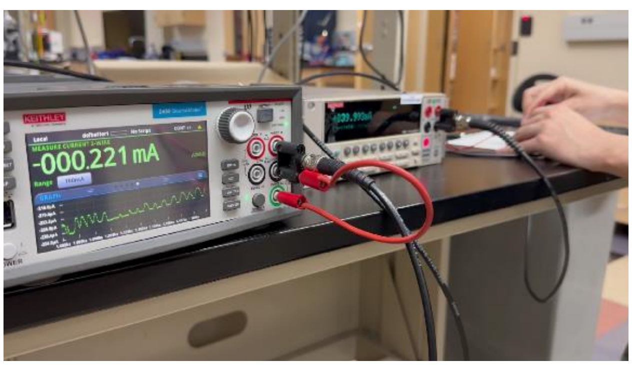


Figure 27 – Laser module test set-up

This basic design, while functional, is not the final iteration as it can be difficult to determine distance from the monitor current on its own. Hence, the reason for the photo-amplifier and comparator circuit that was designed in the last chapter, now in a DipTrace schematic seen below in Figure 28. Where J2 is a two pin header that is providing the current for the laser from the Keithley source meter and J1 is measuring the voltage output of the comparator. Note that components B1 and B2 are banana jacks for the 5V power supply and ground for the components and reference voltage. U1 is the AD8613 CMOS op-amp and U2 is the LT1720 comparator. The reason the AD8613 was chosen is that CMOS op-amps have low input bias currents up to a maximum of 1 pA, so it will not offset the current coming from the photodiode. The LT1720 was selected because of its internal hysteresis and that's optimized for 5V operation.

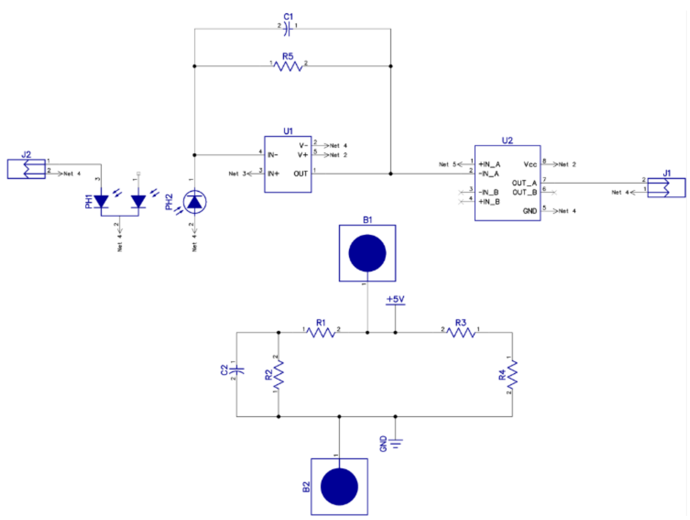


Figure 28 – Range finder circuit in DipTrace

Also, as done for the TILS PCB design the components such as the resistors and capacitors are SMDs to make the board as small as possible as seen in Figure 29 for the PCB layout for the range finder. Another fact to mention is that the laser module will be off the board connected by a twisted wire pair much like the TILS design, hence the vias connected to ground to reduce any voltage noise.

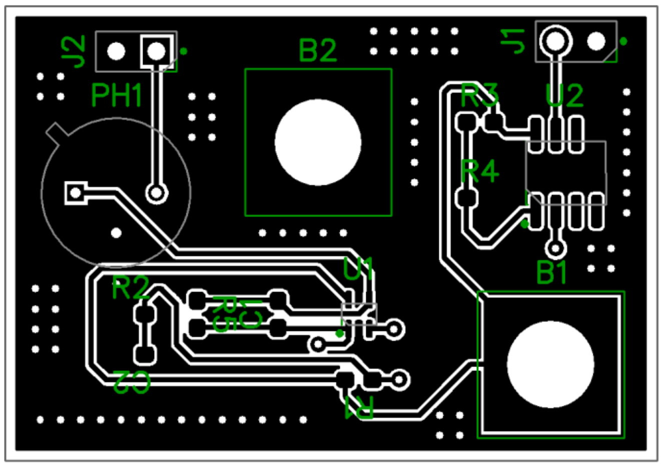


Figure 29 – PCB layout for range finder

While the range finder design finds another useable application for the laser module, the main goal of this thesis is to find another application for the avalanche pulse generator that was designed earlier. To achieve this goal, the range finder circuit is incorporated with the TILS circuit from earlier, seen in Figure 30 and 31, where the PCB board can now perform as a driver for a laser diode and as a range finder. Since the pulse generator can drive the laser diode then the range finder can take the current from the photodiode and get a distance measurement at the same time. It can also just be supplied with constant current to the module to use the range finder.

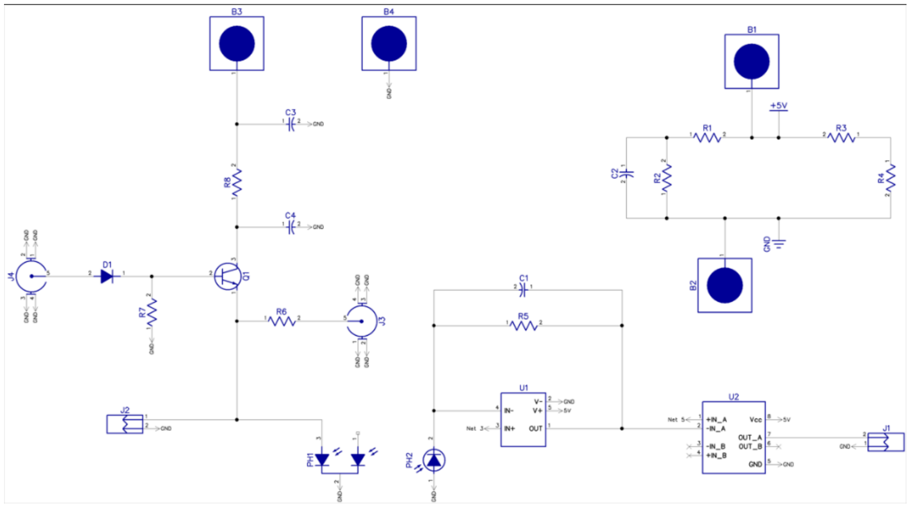


Figure 30 – Single circuit for pulse generator and range finder designs

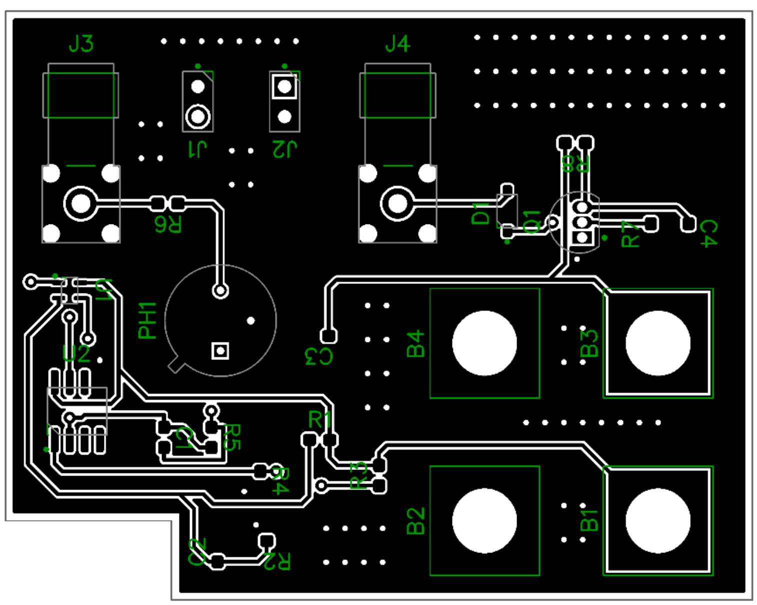


Figure 31 – PCB layout of combined designs

The assembled PCBs for the range finder and combination design can be seen in Figure 32. Where both are used for testing the simulated output that was shown in chapter 6, with the combinational design powering the laser diode and the range finder PCB with a MTD3910PM photodiode, seen in Figure 33. As it was difficult to test the photodiode that was in the laser module with the laser diode at the same time.

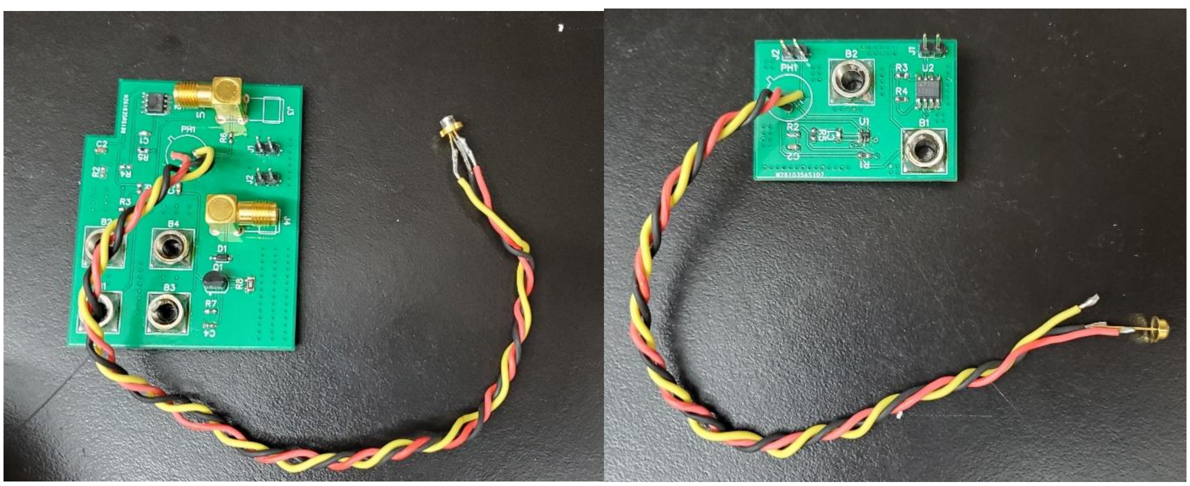


Figure 32 – Combinational and range finder PCBs

With a Keithley source meter providing current to the combinational PCB for the laser and an oscilloscope to measure the output from the range finder PCB, along with a voltage power supply to power the components on the board, see Figure 34.

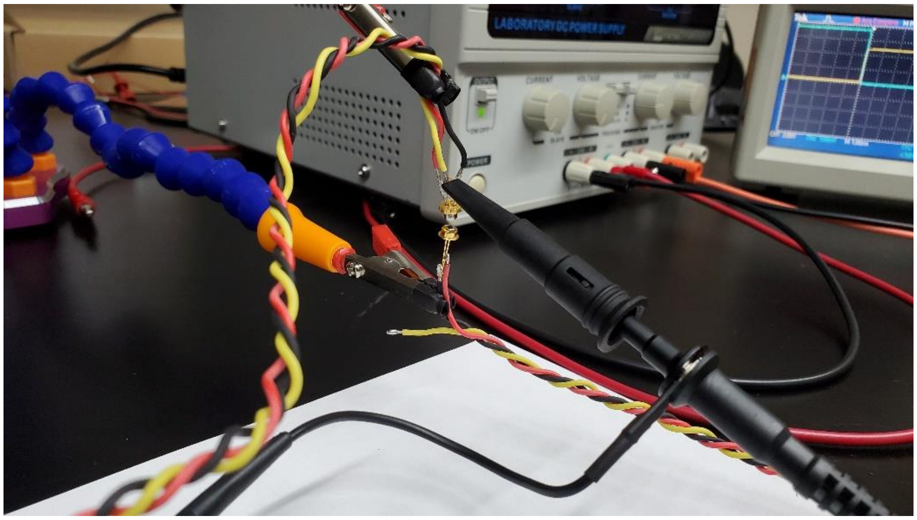


Figure 33 – Laser module distance from photodiode

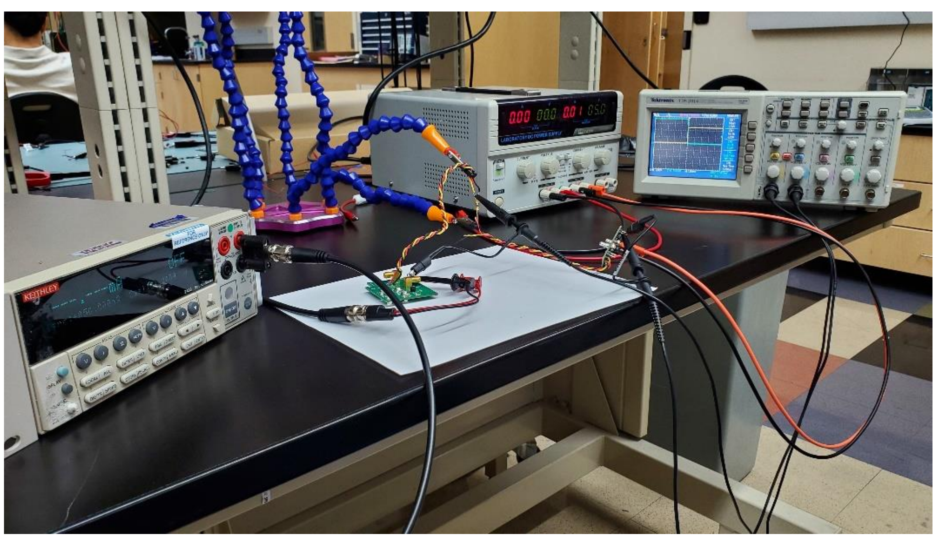


Figure 34 – Test set-up for range finder

The result is the output seen in Figures 35 and 36, which is the output of the comparator going from high to low, indicating that the voltage from the photo amplifier has passed the reference voltage. While the other figure shows the comparator output along with the voltage from the laser diode when it is pulsed. Note for reference, the distance between the photodiode and laser is about half a centimeter. The reason for the distance is due to the relatively short range of the laser from testing the module earlier in the chapter from Figure 27.

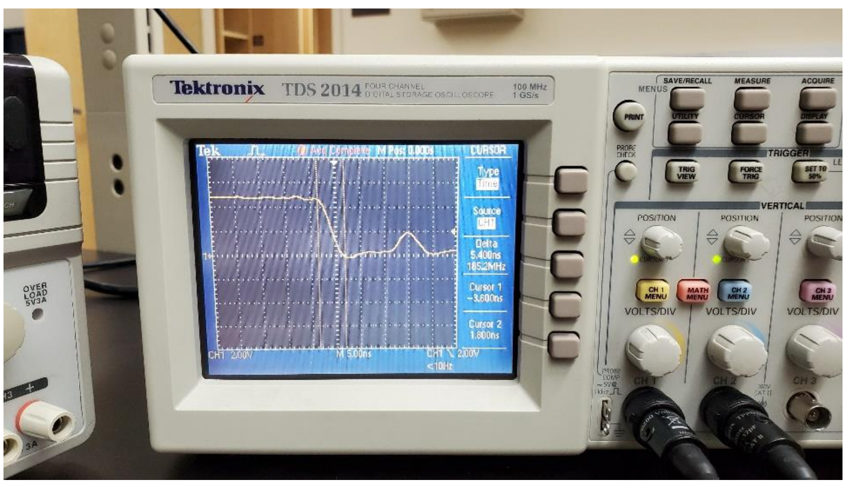


Figure 35 – Output from the comparator on the range finder PCB

With the verification of the range finder circuit now working properly. The only step that remains is to use the pulses from the output of the comparator and from the laser to attempt to measure the distance from the laser diode and photodiode. This method of measurement is known as time of flight measurement, whereby taking the difference in time of the two pulses, it gives the time it takes for the laser to reach an object, in this case the photodiode. By taking that time and multiplying it with the speed of light then dividing it in half, that will give a distance measurement.

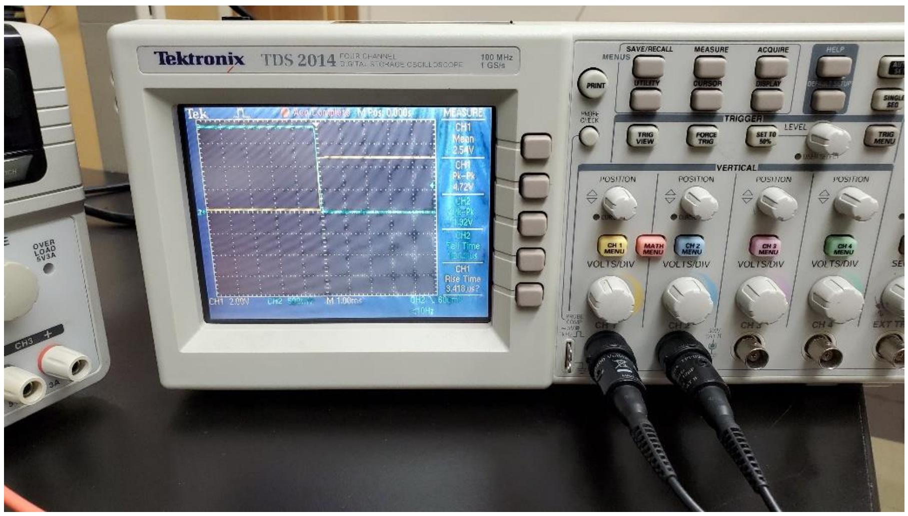
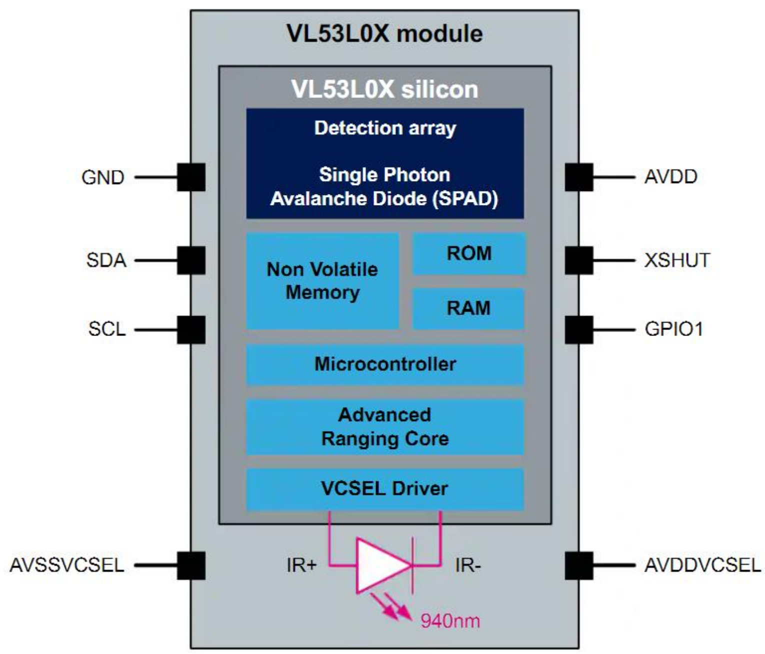


Figure 36 – Time of flight measurement

The time measured between the pulses from the oscilloscope was around 5 ns, putting that in the distance formula gives 0.75 meters or 75 centimeters. Unfortunately, that is not close to the distance from the laser diode to the photodiode that was stated earlier of half a centimeter. Hence, from the testing it can only be stated that the circuit performs as expected from the simulations, but in terms of serving as a range finder it does not give the expected result, at least when using time of flight measurements. A few options may serve as solutions to make the range finder accurately take measurements; two options are not explored but discussed. One is to use an oscilloscope capable of displaying a smaller time scale as the one used in testing only scales down to 5 ns, hence it may be bottlenecked to that time difference from before, but with limited equipment available at the time of writing it is not possible to test this theory. The other is instead of using the oscilloscope for time of flight measurements is to use a microcontroller to measure the time that it takes the laser to reach its target and then calculate the distance. An example of this structure from its datasheet, see Figure 37, would be the VL53L0X a small ranging and gesture detection sensor with built-in microcontroller in the sensor.



[6]

Figure 37 – VL53L0X diagram

The last option is to measure over a longer distance with a more powerful laser. Recalling the previous statement that if the oscilloscope time scale constrained how close the laser can be measured from the photodiode, then the measurements will be more accurate after 75 centimeters (calculated earlier). In Figure 38, the infrared laser diode from before is replaced with 650 nm laser and unlike the infrared laser diode from before it has a much stronger intensity, range, and visible light. Since the 650 nm laser cannot be pulsed with the avalanche board, due to its packaging, an Arduino Mega 2560 is used to power the laser. The PCB for the laser is being held in place, with helping hands, to aim directly on the photodiode and avoid holding the laser board.

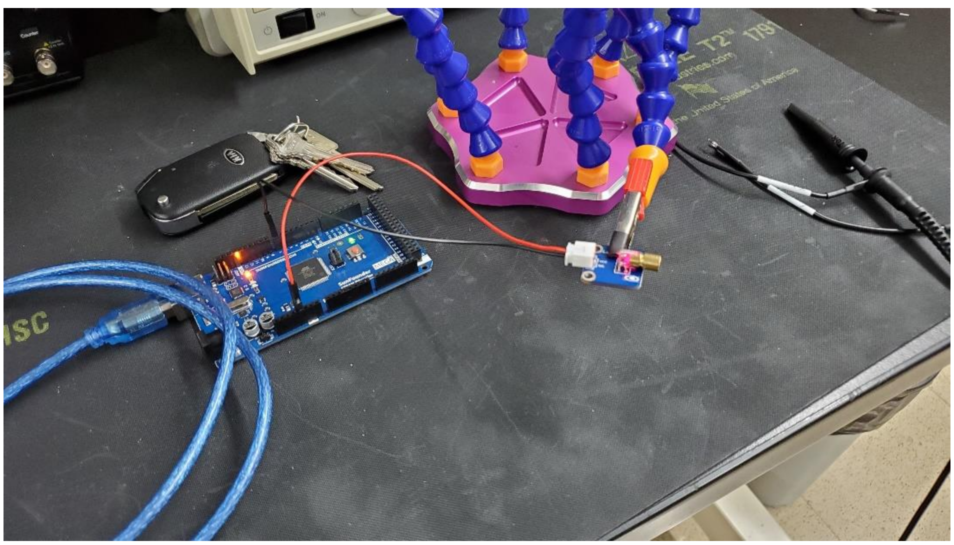


Figure 38 – 650 nm laser powered with Arduino Mega 2560

Now taking the range finder board and setting it in a holder, so that it is directly facing the laser as the light from the laser needs to directly hit the photodiode. Note, this becomes more difficult as the laser is farther away, as will be seen later. The two are then placed about a little more than a meter and a half away from each other, see Figure 39, with the oscilloscope measuring the output of the range finder and voltage of the laser. The voltage power supply from earlier is still powering the range finder the board and a laptop is acting as the control for the laser by sending a control signal from the Mega 2560.

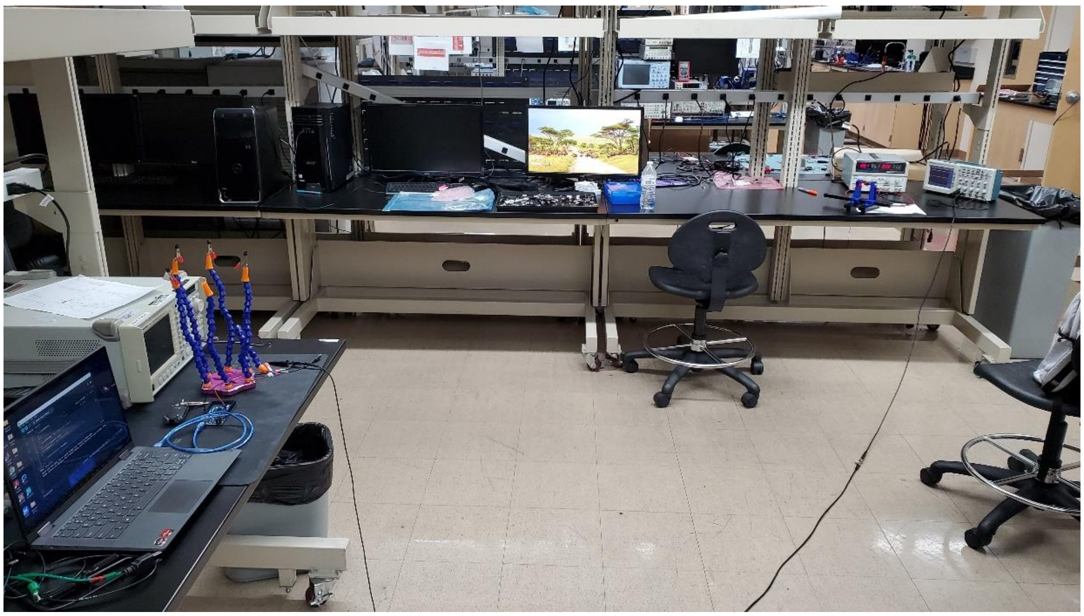


Figure 39 – Test setup for range finding

The output of the range finder is the same as it was before where when light hits the photodiode, the circuit sends a pulse, see Figure 40 and 41. The only difference is the voltage spikes as the output tries to settle, but the spikes are captured by the single frame mode on the oscilloscope once the set trigger voltage is passed. The farther the laser is the more severe the spikes as the light diffuses the farther it travels.

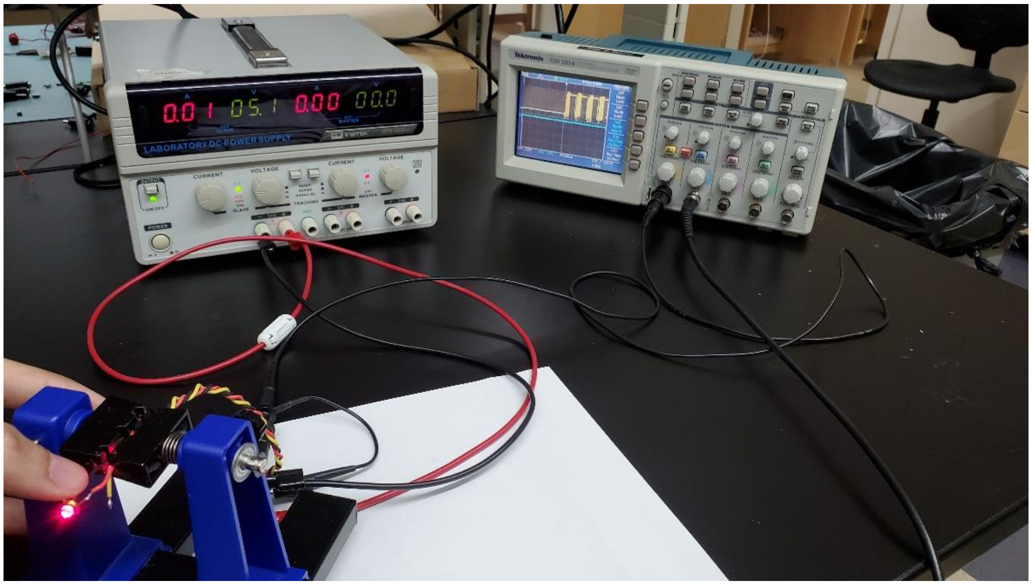


Figure 40 – Laser hitting photodiode

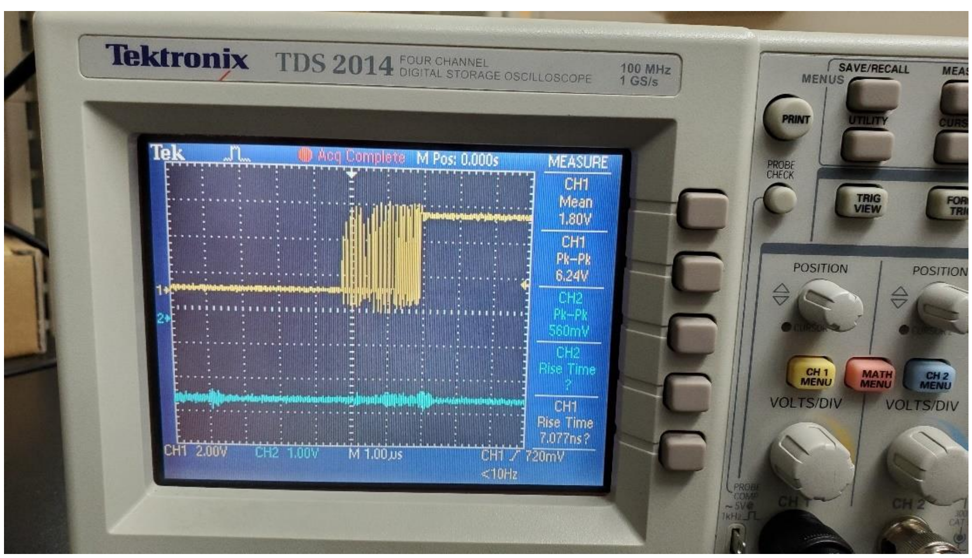


Figure 41 – Range finder output

Taking the same approach for measuring the distance between the laser and photodiode as before, the time between pulses is about 13 ns. The distance from that time calculates to about 2 meters. While this calculated distance is much closer than the previous attempts it is still not a reliable measurement, hence even at longer ranges the range finder still produces measurement error, at least in terms of time of flight measurements using an oscilloscope. A possible source of this error could come from an inherent delay from the electrical components and equipment, but it is unclear from testing where the delay may originate from. Also, tests at longer ranges, such as 3 meters, with the 650 nm laser proved to be unsuccessful as the light was diffused to the point that aiming the laser directly at the photodiode produced no output from the board. To summarize, other than matching the expected output from the simulations, the range finder design cannot, using time of flight measurements with an oscilloscope, accurately measure distance from short or long ranges.

CHAPTER 7 – CONCLUSIONS

Transcranial Infrared Light Stimulation (TILS) is a type of neuron stimulation that involves surgery. A range finder is a device capable of taking measurements of distance using a laser. A device was made that generated the fast-edged current pulse required to perform TILS experiments. Then the device for TILS experiments was modified to use the laser diode and photodiode module with additional circuitry to measure distance. The work documented in this thesis paper analyzes a TILS circuit design for TILS research and a range finder design to expand the applications. A circuit for TILS experiments is comprised of a high input voltage source, capacitor, resistor, transistor, and laser diode. The additional circuitry for the range finder design, an amplifier and comparator, produces an output that when compared to the time of input of the photodiode, a time that can be used to calculate the distance of an object. Each of those components are responsible for a different parameter in the circuit's design and performance. Through testing, experimentation, and feedback from Dr. Hines's research group new additions were made to improve the design. Most notably in the connection between the device and the mouse. Two versions of the device were tested, with the second version being successful in fulfilling the goals of the experiment in effecting the electrical signals in a mouse's brain. While the main purpose of the range finder design is to show that the laser module used for TILS experiments has multiple applications. The range finder device is currently not being used for any research but is meant to show an understanding of the previous work to change it into something else. Currently, Dr. Hines's research group is using this latest version in their experiments in their continued pursuit of advancing and understanding of transcranial stimulation.

REFERENCES

1. Lopez, A., Strong, H. N., McGlothen, K. I., Hines, D. J., & Baker, R. J. (2022). A Compact Avalanche-Transistor-Based Pulse Generator for Transcranial Infrared Light Stimulation (TILS) Experiments. *Instruments*, *6*(3), 20.

2. Baker, R. J. (1991). High voltage pulse generation using current mode second breakdown in a bipolar junction transistor. *Review of scientific instruments*, *62*(4), 1031-1036.

3. Senda, D. (2021). *Designs and Outcomes of Transcranial Magnetic Stimulation (TMS) and Repetitive Transcranial Magnetic Stimulation (rTMS) Circuits* (Doctoral dissertation, University of Nevada, Las Vegas).

4. Baker, R. J. (2019). *CMOS: Circuit Design, Layout, and Simulation*. John Wiley & Sons.

5. Sedra, A., Smith, K. C., Carusone, T. C., & Gaudet, V. (2020). Microelectronic Circuits 8th Edition.

6. STMicroelectronics, “World’s smallest Time-of-Flight ranging and gesture detection sensor,” VL53L0X datasheet, May. 2016 [Revised April. 2018].

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