Faux Laser Audio Signals Detected from a MEMS Microphone

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Abstract

This project aims to explore the photoacoustic interaction between laser light and MEMS (Micro-ElectroMechanical Systems) microphones and how this can be manipulated with voice controlled devices. To do so, I attempted to use laser light controlled by an amplified digital signal and a transistor projected onto a MEMS microphone, but to no avail. The second and current attempt, I decided to control the laser with a driver that modulates the current going through the laser by an analog input. Without proper materials, the results are inconclusive; however, I have hope in the upcoming weeks that a new laser and the laser driver will be able to send a sound signal to the microphone.

This is an interesting and very important experiment considering how incorporated voice-controlled systems have become within our homes. The plausible possibility that someone can control a smart speaker or other device silently and from a distance is extremely dangerous, especially when door locks, window curtains, and even garage doors are connected to these speakers.[1] If some kid in high school with minimal experience in electronics and $100 dollars of equipment can open and close someone's doors with ease, what's to stop more experienced people with more slimy motives?

History of the Photoacoustic Effect

The photoacoustic effect was first noticed by Alexander Graham Bell when he reflected intermittent sunlight onto a selenium solar cell and noticed an emitted sound. He later devised an experiment where he placed a diaphragm of a solid in an audio tube and flashed light onto the solid. He noticed that the material absorbing the light altered the sound transmission and thus deduced that photoacoustic effect occurred due to the absorption of light. He later invented a device that uses infrared light to detect certain molecules in the air. In the 1930s when sensors became more sensitive, this effect was used to detect carbon dioxide in a sample of gas.

This effect has been used in other areas of science like to aid spectrometry of low density gasses. By sweeping the air with a laser at the speed of light, the particles that absorb the laser's frequency and create a sound pressure which can be recorded.[2] The military has also developed a laser that rips apart atoms into a plasma field and then using another laser they manipulate the plasma to emit light and sound.[3] The photoacoustic effect lies in the frequency of the second laser light and how it interacts with the plasma.

History of Voice Controlled Devices

Voice controlled (VC) devices have become increasingly more common in the tech industry. In these devices, microphones are constantly recording to detect trigger words that are used to "wake-up" the device to a specific command. This system allows a user to remotely control a certain appliance or application with just their voice.

The first recorded voice recognition tool was created by IBM in 1961, but it could only recognize 6 words. In 1990, Dragon released the first speech recognition software to consumers and in 2011 Apple introduced Siri into the market and then the VC revolution began. By 2017, Amazon and Google had smart speakers in the market.[4] In 2018, around 24% of the 2000 US consumers surveyed said they owned at least one smart speaker and are thinking about incorporating it more with other household appliances.[5] As of today, millions of speakers have been sold and the numbers are still increasing as markets open around the globe. Data from a survey suggest, "the worldwide smart speaker installed base will exceed 200 million in 2019 and climb to over 500 million by 2023."[6] This smart speaker market has grown simultaneously with smart devices like ovens, doorbells, thermostats, and locks. A report from Statista displays that 11 million smart locks, 599 million smart detectors like smoke, thermostat, smart switches, and other, and 20 million smart light bulbs have been sold in the U.S. and worldwide in 2017-2018.[7]

History of MEMS Microphones

The first usable microphone was developed by Thomas Edison in 1886. This microphone contained two conductive parallel plates with carbon filament in between. When the diaphragm in the mic vibrates to the sound pressure, the carbon particles move around and change the capacitance. In 1916, E.C. Wente developed the condenser microphone which used a vibrating capacitor plate in order to output an electric signal depending on the sound pressure vibrating the plate.[8] The MEMS microphone is similar to a condenser microphone except it is extremely small and is built using MEMS technology. Smart speakers use these microphones because they are small and so the smart speakers can be more compact.

Theory

Physics of Laser Light

Laser, short for **l**ight **a**mplification by **s**timulated **e**mission of **r**adiation, is a way of emitting light by exciting atoms with current in specific glasses, crystals, and gasses. When these atoms are excited, they absorb energy causing electrons to jump shells, and when the electrons drop down to the shell nearer to the nucleus, a photon is emitted at a frequency proportional to the energy difference of the drop. Because the material is constant and the atoms in the material have a limited number of shells, the wavelength of the photon is constant. Surrounding this material are mirrors that reflect the photons in such a way so that the photons hit other excited electrons. This causes the atom to release more photons and a chain reaction occurs. The mirrors help direct all the photons into a specific direction creating a tight, focused beam.[9] In my project I will focus on laser diodes found in common laser pointers. In a laser diode, p-type and n-type semiconductors are placed next to each other. In a p-type semiconductor, there are more areas for electrons to move than electrons themselves so these empty areas carry most of the current charge. In an n-type semiconductor, there are more electrons than areas for electrons to move and thus the electrons carry most of the current charge. When these two semiconductors are placed next to each other, a P-N junction forms. When current is sent through these conductors the positive “holes” in the p-type move towards the junction and the extra electrons in the n-type move towards the junction as well. At this junction the electrons combine with the holes, but the electron is at a higher energy state than the hole and must therefore lose energy to group with the hole. The energy released is in the form of a photon and this photon will hit other excited electrons causing them to emit two more photons. Surrounding these semiconductors are highly reflective plates that bounce the photons millions of times back and forth causing more electrons to emit more photons and thus amplifying the light even more. A small, partially reflective end of the laser diode emits light in a straight beam preventing the beam from spreading out to a very large degree. The materials used in these semiconductors are commonly Gallium Arsenide (GaAs) and Indium Phosphate (InP).[10] The laser requires a driver which sends a stable current through the diode, which is important because the current determines how much charge (electrons) is flowing and therefore how many photons are released. In order for lasers to heat up an object, the molecules in the object absorb the photons emitted from the laser. These molecules absorb this energy as Kinetic energy thus causing the molecules to wiggle and thus the object heats up. This is similar to microwaves, except in microwaves, the waves are wiggling water molecules which end up bumping into the other molecules in the food and boom, a warm TV dinner! Metals heat up especially quickly because metals have more free moving electrons which are more easily wiggled by absorbing photon energy.

Physics of MEMS Microphones

MEMS microphones use the science of a capacitor to convert audio into electrical signals. They do this by using a capacitor with one flexible plate that changes due to audio pressure, and thus the potential difference changes creating a varying electrical signal related to the audio wave. A capacitor is a circuit component with two parallel plates and a dielectric in between the plates. A dielectric is a material that loses its conductivity when an electric field runs through it. When a current is sent into the capacitor without anywhere for the charge to go, opposite charges develop on opposing plates. The charges create an electric field that runs from the positive plate to the negatively charged plate, or through the dielectric. This prevents charge from moving which charges up the capacitor. The electric potential of the capacitor is inversely proportional to the capacitance and proportional to the charge held on the capacitor. The capacitance of a capacitor is inversely proportional to the distance separating the plates, and thus the voltage is proportional to the distance separating the plates. When the sound waves hit the on of the conductive plates, the plate moves closer to the other parallel plate creating a change in voltage. The recorded voltages are later converted into audio. $C = \frac{q}{V}$ $C = \epsilon_0 \frac{A}{d}$ $V \sim d$

When a metal is heat up, synonymous with particles within the metal vibrate and gain more kinetic energy, the forces holding the atoms together weaken as the vibrating particles are harder to control. This causes the molecules to move away from each other so that at the larger scale, the metal expands. One theory is that when the laser hits the microphone, the diaphragm heats up and thus expands and contracts as the laser beam intensity increases and decreases creating a vibrating pattern similar to an audio signal.

Physics of the Arduino

The Arduino is a type of microcontroller that can process input voltages, send out voltages, and communicate with other computers. The Arduino takes in voltages from 5V to 3.3V and translates this voltage into a binary number from 0 to 1023. This is because the Arduino can only process 8 bits of information, 8 binary pins, or 2^8 combinations (1024) of on and off. When a voltage comes in at 5V, the Arduino will record this as 1023 and if the voltage comes in at 0V, the Arduino will record this as 0. Code can then be written to interpret, record and output current based on certain inputs. The Arduino can output varying analog voltages from 0V to 5V using a pulse width modulator. A pulse width modulator alters how frequent a signal is on versus off extremely fast to make it seem as if the voltage decreased. For example if 70% of the time the signal is off, the voltage appears to be 70% of the max voltage. This is done using square waves which create a distinct on and off pattern.[11]

Theory of .wav Files

WAV stands for Waveform Audio File Format and it is used to store an audio bitstream. In a .wav file, audio is stored using linear pulse code modulation. By sampling audio at uniform intervals, the amplitude of the wave is recorded to the nearest digital number storage and saved. For this experiment, I will most likely be using the .wav format because the linear pulse code modulation is similar to recording input values from an Arduino and outputting values from an Arduino. This will allow me to send audio files directly to the laser driver to modulate the current as a function of the voltage coming in from the file.[12]

Theory of Thermoelectric Cooling

The thermoelectric effect often known as the Seebeck-Peltier effect involves the conversion of thermal energy into a voltage difference. The Seebeck effect was discovered by Thomas Johann Seebeck, who noticed that a magnetic field occurred at the ends where two different conductors were connected. A way to visualize this is to imagine an oreo with chocolate and vanilla cookie disks, connected at opposing ends by a rod. The fields were created by currents at the ends of these rods which resulted from a temperature difference in the conductors. A potential difference can be created if the temperature difference remains, however the conductors do not have current flowing through them.

When a physicist named Jean-Charles-Athanase Peltier sent current through a conductor junction similar to the one Seebeck used, he noticed a temperature difference unrelated to normal ohmic-heating losses. It was discovered later that changing the direction of the current through the conductors changed the direction of heat transfer.[13] Currently, manufacturers use alternating p and n type semiconductors, which have a complementary heat transfer direction, to heat and cool low to medium heat pumping applications.[14]

Theory of DC Power Supplies

Many circuits require direct current to function, however the electricity coming into our homes is alternating current. This calls for a DC power supply which converts the alternating current into direct current. Direct current is the flow of charge in a single direction. Alternating current is the movement of charge back and forth at a certain rate or frequency. This is commonly seen as a wave with positive current going one way and negative current going the opposite. A DC power supply uses a system of diodes, which restrict the flow of charge to one direction, in such a way that no matter the direction of the alternating current, a constant, single-direction current is emitted from the diode system. The AC running in our house is also extremely high at 120V, whereas I normally have the power supply output a voltage less than 10V. To lower the voltage, a step-down transformer is used. A step-down transformer has two ends wrapped with coil, except one end has less coil wrapped around it than the other.[15] When current travels through the side with more coils, a magnetic field is created and induces a current in the side with less loops. Since the side has less loops, the magnetic field acting on the wire is less and so less current flows. This creates a lower voltage, and so it is more manageable to deal with.[16]

Theory of Circuits

Current, voltage, resistance, capacitance, and inductance are five of the most important factors to look for in a circuit. Current, as explained earlier, is the flow of charge in one direction for DC or oscillating charge for AC at a certain frequency. Voltage, also known as electric potential, is the amount of potential energy per unit charge. This means that a charge +q at 5V has 5 joules of energy. Resistance is the impedance of current flow created by electrons bumping into molecules in the resistor creating heat. In a circuit the voltage across a resistor is equal to the current through the resistor and its resistance. The amount of energy an electrical component takes per a certain amount of time is called power and is referred to as a Watt. The wattage of a component is equal to the voltage across it multiplied by the current, so it is important to be mindful of these things when using a laser diode. A voltage too high could increase the wattage of the diode causing it to burn out and it could also be too little to power the diode.

Capacitance is the amount of charge stored on two seperate but opposing conductive plates/sheets. When positive charge gathers on one side of the plate, positive charge on the other plate is pushed away creating a negatively charged opposite plate. This creates an electric field which creates an electric potential across the two plates. A capacitor can then be discharged, however it discharges almost immediately unless a resistor impedes the flow of charge.

Inductance is the storage of energy in the form of a magnetic field which opposes the flow of current. These magnetic fields store energy until current no longer flows, and then the energy stored in the magnetic field is converted back into electrical current.[17]

Theory of the Digital Storage Oscilloscope

A digital storage oscilloscope allows a user to see the voltage at a certain point in a circuit over a certain amount of time. In a digital storage oscilloscope, a voltage is sent into a channel input on the oscilloscope. Then, the signal is amplified and converted into a digital signal. This is done using an analog to digital converter which reads in an analog voltage at a certain time and stores it as a digital value. The amount of voltage samples the oscilloscope takes in over a certain amount of time is called the sampling rate. This data is then plotted on the screen of the oscilloscope for the user to see the voltage versus time.[18]

Theory of the Digital Voltmeter

The voltmeter is also a very important sensor for circuits. Unlike the oscilloscope, the voltmeter outputs a single digital reading of the voltage in that instant. It contains an extremely high resistance value in order to take a small amount of current from the circuit. Since two resistors in parallel have the same potential difference across them, the voltmeter when placed across a resistor calculates the potential difference by multiplying the internal resistance by the current flowing through. This value is converted into a digital value and displayed on the screen of the voltmeter.

Experimental Design

The first step was to use a MEMS microphone and connect it to a speaker to hear if the laser light could create any sound at all. To do this I used an MEMS microphone breakout board and connected it to an audio amplifier which drove a speaker I took out from a Google home (Figure 1).

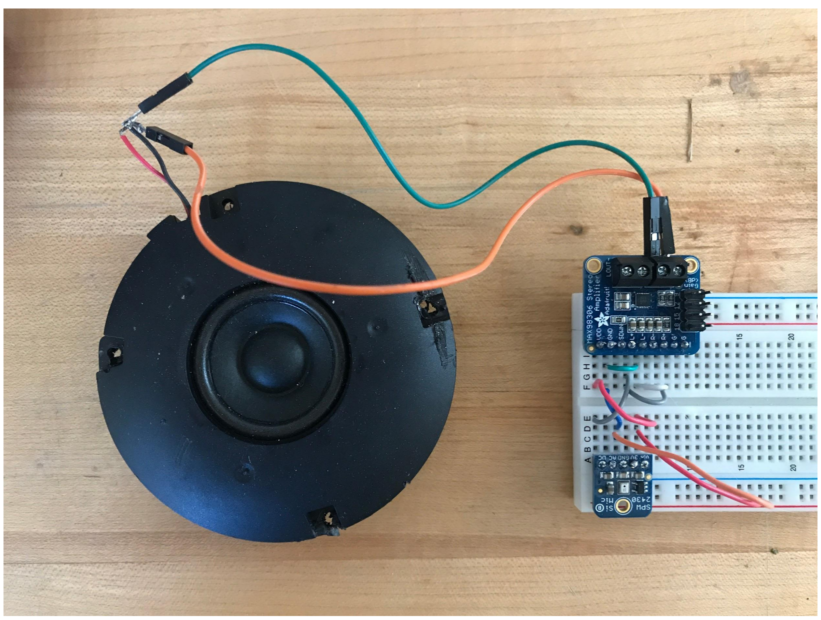

Figure 1: MEMS microphone (bottom right), audio amplifier (middle right), and speaker (left) circuit.

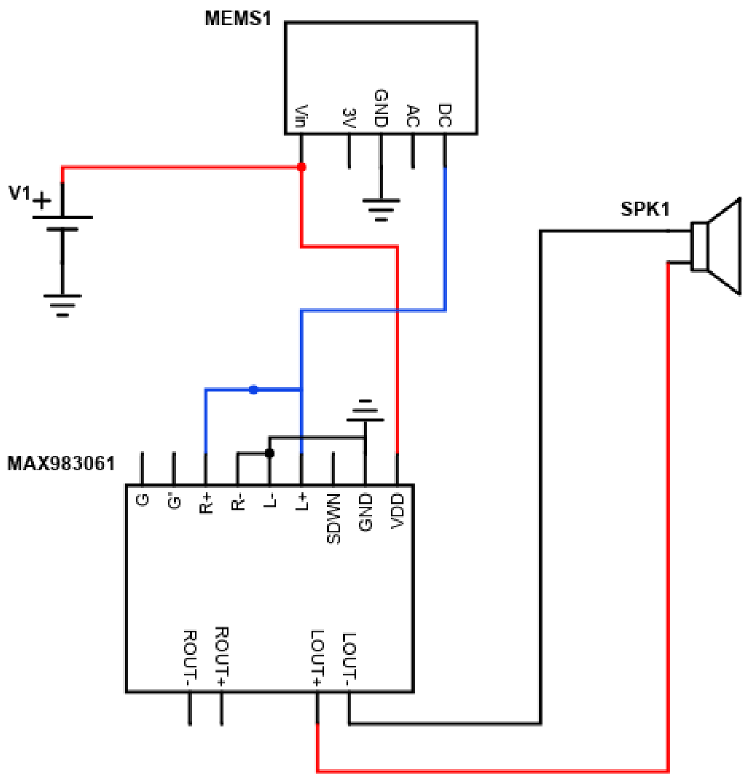

Figure 2: Microphone-Speaker circuit

The microphone breakout board and the stereo amplifier board are connected in parallel to a DC power supply at 5V. When the microphone picks up an audio signal, it outputs an analog voltage waveform from the DC port. This signal is not powerful enough to drive the speaker I used, so I connected the microphone output signal to a stereo amplifier. The amplifier has two inputs, L+ and R+, to drive a surround sound system; however, I only needed to drive one speaker so I connected the L+ and R+ together so they have the same output. I arbitrarily chose the output pin to be L_{out}, which I hooked the V_{in} of the speaker to. After testing to make sure the microphone output was audible, I moved on to sending audio via laser light.

Sending a .wav file out from an Arduino may still be a possibility, however there were few resources detailing how to use .wav files with Arduino so I decided to move on.

I then wondered if my computer audio would be able to drive the laser itself, thereby cutting out the Arduino middleman and making the whole system much simpler. Unfortunately, the voltage coming out of the audio jack was nowhere near high enough to drive the laser. To fix this issue I used an op-amp circuit to increase the voltage 10 fold (Figure 3).

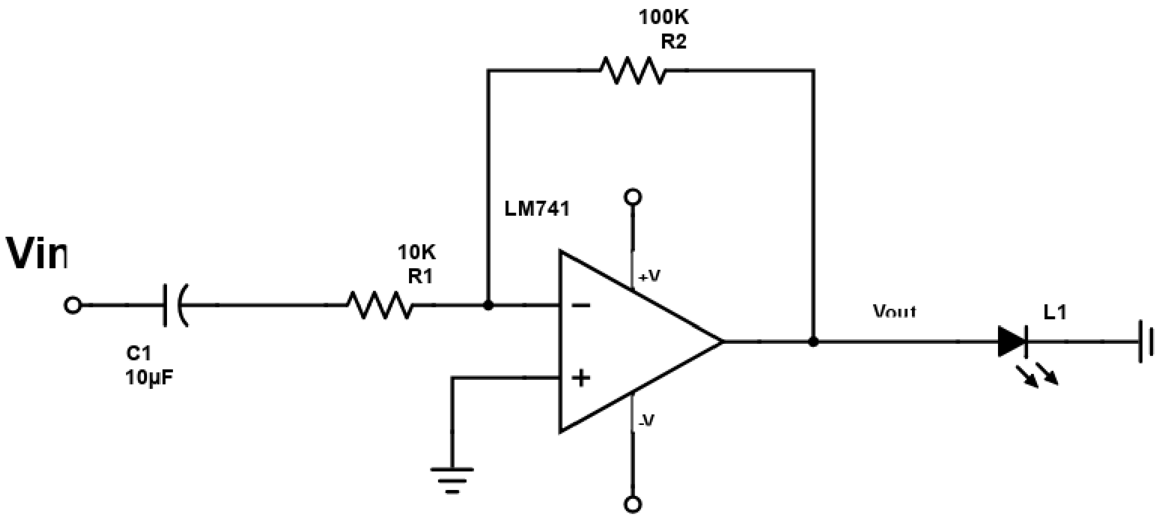

Figure 3: Op-Amp circuit with a gain of 10 using an LM741

The op-amp uses a LM741 amplifier, and this circuit provides a gain of 10 (100,000KΩ/10,000KΩ) to the input voltage (Figure 3). The input voltage I measured maxed out at 5mV, so a gain of 10 would provide an output voltage peak at .05V. A 10µF capacitor is in series with a 10KΩ resistor to pin 2 of the LM741. The capacitor gets rid of any DC voltage offset, so a pure wave is sent through. A 100KΩ is placed in parallel with pin 2 of the LM741 and the output voltage at pin 6. The +V input and -V input are hooked up to a +15V and -15V power supply, respectively. I used an LED connected in series to the output voltage pin 6 at first to see if a modulation in the intensity of the light occured. The reading on the oscilloscope across the LED displayed the AC signal was amplified properly. When using an AC generator and an LED, the light flickered on and off similar to the sine wave. Unfortunately, when replacing the LED with the laser module, the amplified signal was not strong enough to power the laser module. It may have been possible to increase the gain to 1000 in order to get a peak voltage at 5V, however this will create a much fuzzier analog signal. Since I want to be able to control smart speakers in the future, I needed a way to drive the laser using a clear analog audio wave.

After reading more about the Michigan researchers' project, I read that it would be best to use a current modulating laser driver. It is important for lasers to have a constant current driver rather because the voltage across a laser diode increases as the laser diode heats up during use. This causes the laser to draw an exponential amount of current (Figure 4).

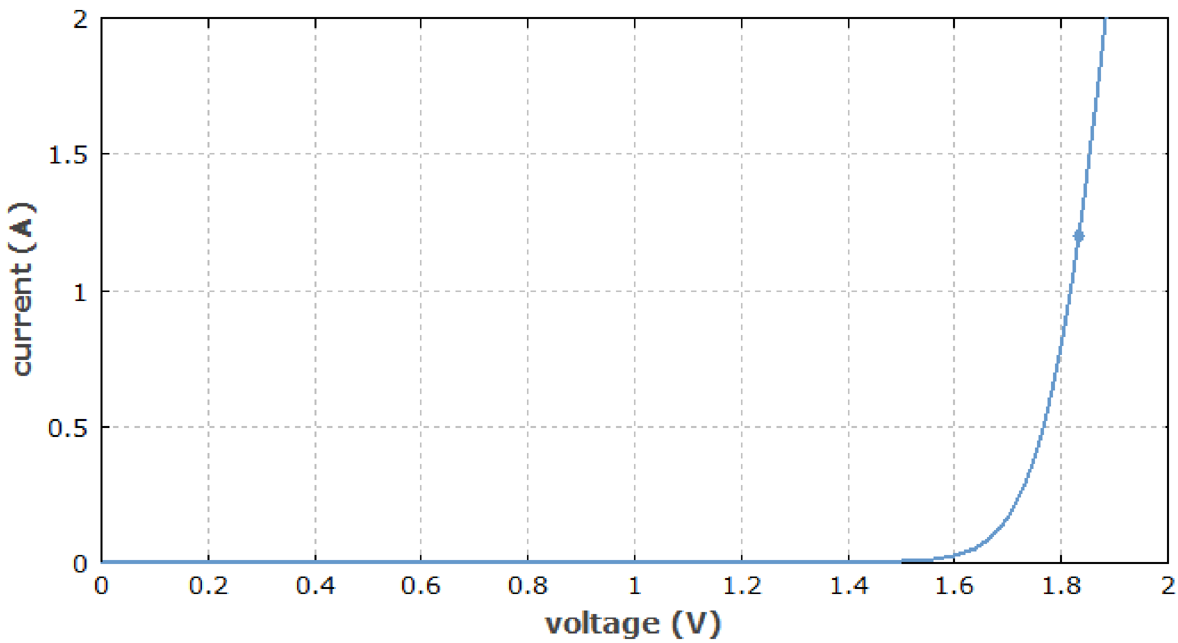

Figure 4: Current vs. voltage of a laser diode. Source: RP Photonics,
https://www.rp-photonics.com/laser_diode_drivers.html.

I purchased the LPLDD 5A PID Laser driver for this task. This driver has on board current limiters in order to set the peak current I need for my laser driver. It requires a heatsink for two MOSFET transistors on the bottom of the driver, so I used a heatsink I found in multiple usb port device and a heatsink made from an aluminum can (the loose, aluminum can heatsink is most likely the cause for future problems which will be covered later) (Figure 6). To use this driver I connected to it a laser diode module, a DC power supply, and a TEC module (Figure 7). My initial thought was to use my computer audio, boosted up by the op-amp, to send the audio signal to the laser driver (Figure 5).

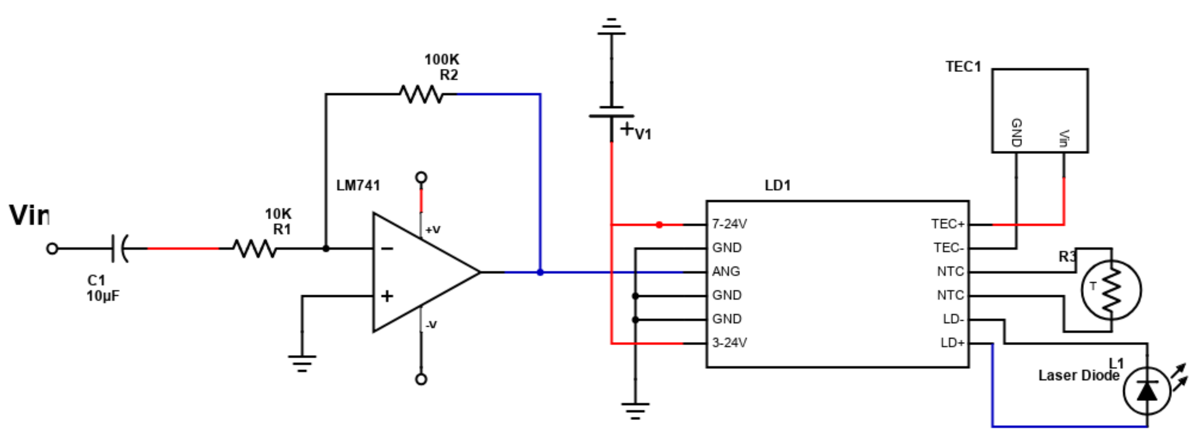

Figure 5: Op-Amp circuit connected to laser driver to drive a laser diode.

My initial desired circuit uses the op-amp circuit, except the output voltage signal is sent to a more powerful laser driver which uses an analog voltage modulation from 0V to 5V to modulate the current going through the laser (Figure 5). The driver is powered by a DC power supply. There is a potentiometer onboard to set the max current, as well as a port to view the output current with a voltmeter/oscilloscope. There is a TEC port to power a thermoelectric cooler as well as a port for a thermistor. These systems are present to protect the laser diode from burning out. The laser diode is then connected to the LD+ and LD- pins.

Since my computer audio port broke (most likely because I fed 10V into it), I used my guitar amp which was able to output a 2.5V signal instead of the op-amp (Figure 6, Figure 9).

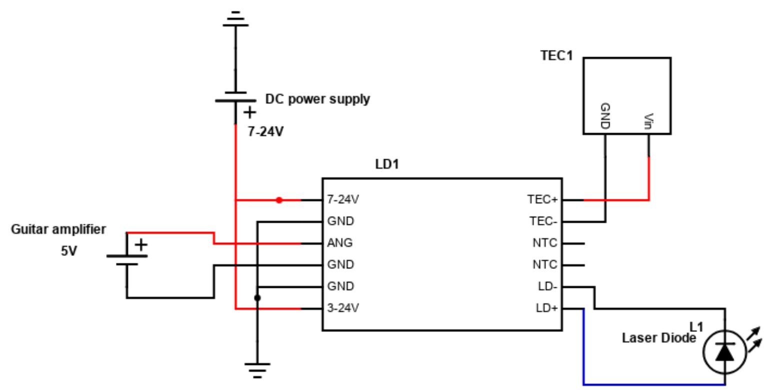

Figure 6: Guitar amp signal sent to laser driver.

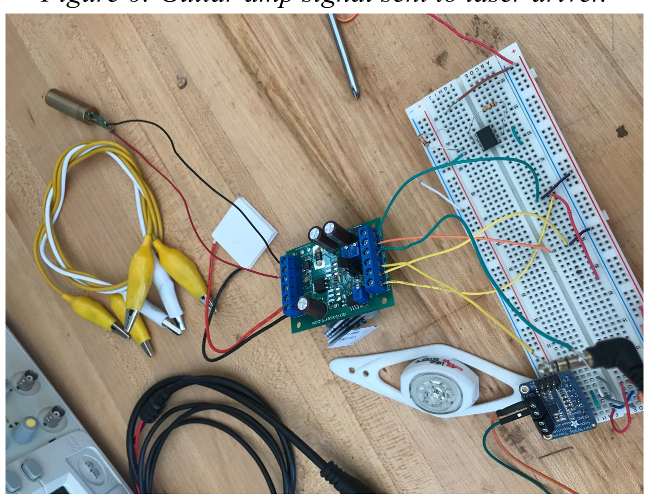

Figure 7: Audio jack (right) connected to laser driver (center).

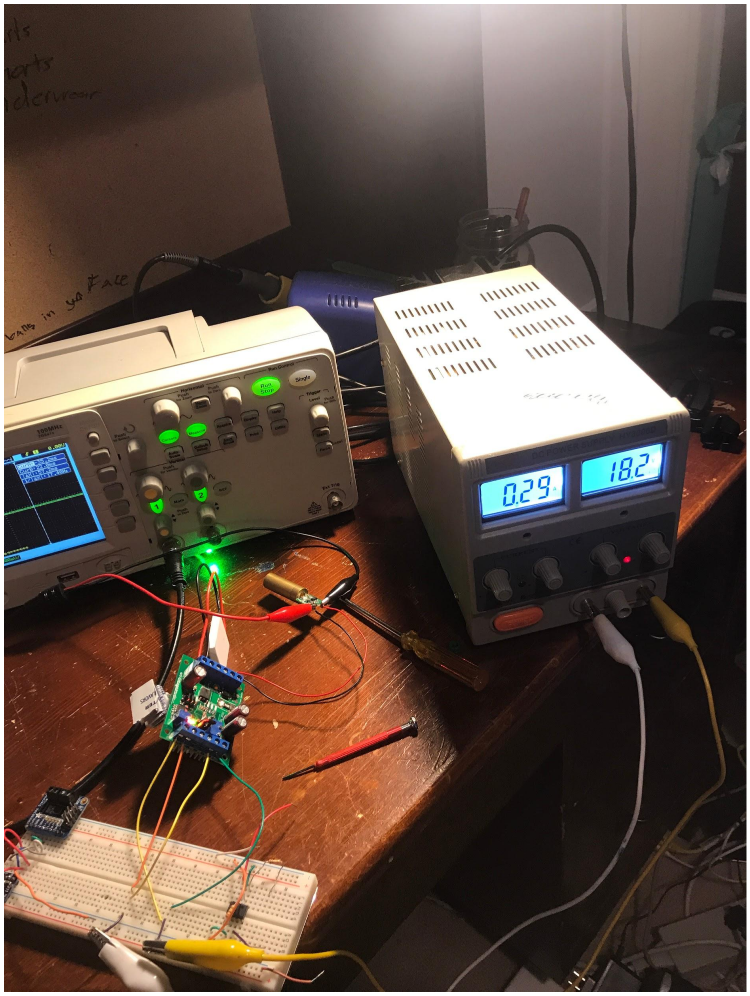

Figure 8: Laser driver properly driving the laser diode. Not connected to guitar amp.

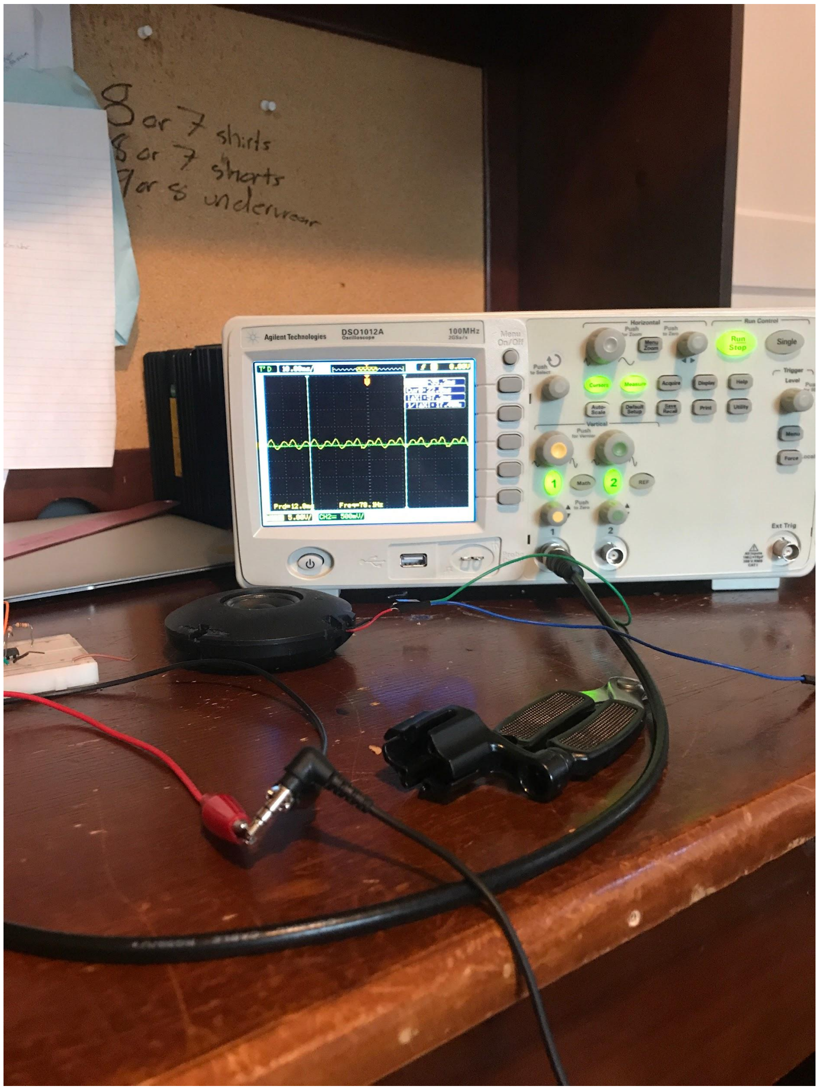

Figure 9: Audio jack signal connected to oscilloscope.

Unfortunately the laser diode burnt out and the replacement laser did not come in time. I tried using an LED array to test the driver's output based on an incoming signal. I was able to get a fair amount of power to the LED's, however after a short amount of time the LED intensity dropped and then died. It is likely that these also burnt out because the DC power supply will not turn them on. The other idea is to use a power resistor and detect the voltage drop across it which is proportional to the current going through it. Since the voltage across a resistor is equal to the resistance multiplied by the current, I will be able to tell if the driver is properly modulating the current, based on the analog input, if the voltage signal from the amp (Figure 9) is seen across the resistor. This will also allow me to test the driver without potentially damaging the laser diode.

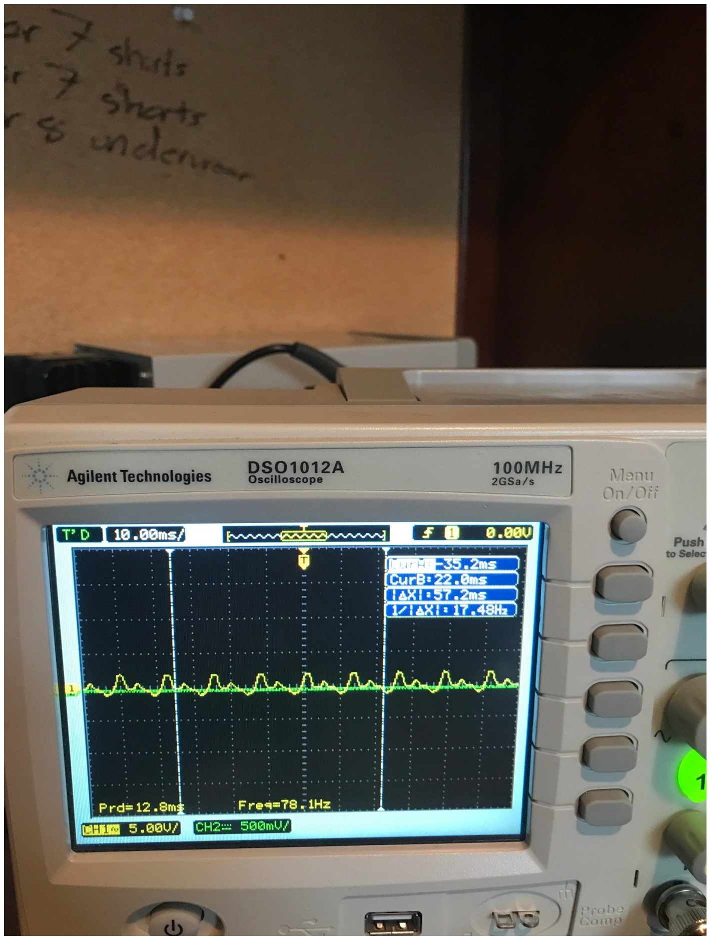

Figure 10: Oscilloscope reading of guitar note from amp.

Results

The laser driver could drive a green laser diode at a constant current when powered at 18.2V and drawing .29A of current (Figure 8).

The guitar amp outputs a peak voltage at +2.5V (Figure 10) when the gain is turned to the max (Figure 11).

Figure 11: Guitar amp gain knob (second to left) set at the max level.

Compliance Voltage	3,3 - 24 V
Dimensions	58 x 45 mm
Max Ouptut Current	5 A
Max. Modulation Frequency	100 kHz
Max. Power Dissipation	15W
Max. TEC Current	15 A
Modulation Input Voltage Range	0 - 5 V
Mounting Hole Spacing	38 x 48 mm
Pre-Set Current Setting	2000 mA
Softstart Time	2000 ms
Temperature Sensor Type	10k NTC thermistor
Transistor Type Used	N-MOSFET
Temperature Stabilization Accuracy	±0,1 °C
Rise Time	less than 1.5μs
Fall Time	less than 1.5μs
Noise and Ripple (RMS)	12.5 mA
Minimum Current (3% Noise)	500 mA

Table 1: Laser diode data sheet. Source: https://optlasers.com/medium-power-drivers/lpldd-5a-24v-pid

Conclusion

Ultimately, I was unsuccessful in producing audio in the MEMS microphone using laser light. This is mainly due to the fact that I was unable to properly modulate the intensity of the laser light based on an incoming analog signal. Despite the goal of the project not working, several things were able to work and give me hope. The guitar amp was able to send out a 2.5V signal from an audio source (Figure 10). Though the guitar amp is not very mobile, it will still be helpful in testing. The laser driver also works using the test port to output the max current (Figure 8). The microphone and speaker system work properly. The main source of failure is the laser diode not working, and without the power resistor it is unclear whether the output of the laser driver is modulated by the input analog signal.

Next Steps

I will definitely continue with this project, however I will make some changes. The first change is I will be using an Arduino. I feel like I gave up too quickly with it, and lost sight of what I truly wanted to do. The main goal in the back of my head was to use cheaper electronics to have the same result as the more sophisticated electronics used by the Michigan researchers. The Arduino can also output a 5V signal which is perfect for the laser driver.

The first step would be to use the Arduino to output a 5V .wav file and test by using the oscilloscope to detect the voltage drop across a resistor. This requires the Arduino to access a .wav file from an SD card. I will simply use an SD card breakout board and connect to the Arduino. There is an audio library for the Arduino that outputs .wav files accessed from an SD card which I will be using for my project. Then, I will send this signal to the laser driver which has a sampling rate of 100kHz. The Arduino has a sampling rate of around 10kHz so this is more than enough[19]. I would like to purchase the much smaller driver meant for lower power driving (around 1.5W), because it is cheaper and smaller. This is important because if I end up trying to break into homes, I will need something that is more discreet.

Acknowledgements

I would first like to thank Mr. Formato for giving me the idea to take on this project. Secondly, I would like to thank Dr. Dann for his suggestions and interest in my project. It helped me stay motivated throughout the process and he always put me in a good mood no matter how much my project seemed like it would not work. I would also like to thank Dr. Dann and Mr. Ward for letting me take home expensive instruments including the oscilloscope, soldering iron, and DC power supply. I definitely would not have been able to continue working on my project without them. The weekly check ins during quarantine also kept me motivated; so special thank you to Dr. Dann for setting those up.

I would like to thank my A-block class for inspiring me to work harder. Seeing everyone progress was amazing and I was motivated to show my peers what I could make. I also appreciate the humor from this class because it lifted my spirits and eased my stress.

Lastly I would like to thank my Dad for always pushing me and asking questions to keep me thinking. It helped me to see the flaws in my project so I could progress.

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Appendix A

Purchased parts list:

Part	Cost
Laser Pointer	12
laser goggles	65
SPW 2430 MEMS	4.65

microphone	
MAX98306 Stereo amplifier	8
LPLDD 5A PID Laser driver	70

Other parts list:

- LM741
- DSO1012A oscilloscope
- Green laser module
- HY3006D DC power supply