Experimental Design and Measurement of a Novel 2.5-2.7 THz Amplifier

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Abstract

The University of Southern Indiana (USI) is partnering with the Jet Propulsion Laboratory (JPL) to design, build, and test a new amplifier at 2700 GHz. No amplifiers currently exist anywhere near this frequency. The USI student research team designed an optical testbed to measure amplification from this new type of amplifier built from a quantum cascade metasurface (QCMS). The QCMS is a specially designed semiconductor material that resonates photons producing amplification of a monochromatic source. The main design component of the optical testbed was the design and fabrication of an elliptical mirror block. The reason an elliptical mirror was chosen is that it allows for the source, amplifier, and detector to be positioned at the foci of the mirror and for the source to be reflected into the amplifier, and then the amplified light beam reflected onto a detector.

The team has taken two trips to JPL. In first trip during the summer of 2023, they used a frequency multiplier chain (FMC) that operates at ~2500 GHz as the source and using the QCMS amplifier they successfully measured ~2 dB. Building on this result, JPL and USI decided to try a different source called a quantum cascade laser (QCL) that operates similarly to the QCMS amplifier. The advantage of the QCL is that it has more initial power than the FMC, but a different radiation pattern. Based on this new radiation pattern, the team designed a second mirror block that was tested in spring 2024. They also characterized the frequency and radiation pattern of the QCL. This paper will discuss the design and fabrication process, the measurement setup, and results of both the QCMS amplifier from summer 2023 and QCL from spring 2024.

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I. Introduction: Terahertz Waves and Their Importance in Galactic Astronomy

The emission of terahertz (THz) waves as spectral lines from gas clouds in star forming regions in space is a rare occurrence. However, given the vast quantities of gas and dust in space, they are far more commonly observed than anyone originally thought. THz waves are emitted from certain elements when an electron transitions from a higher state of energy to a lower state because of interactions between the orbital motion and spin of the electron, also known as fine structure lines. As this transition happens the electron releases energy in the form of a photon equivalent in energy to a THz wave.

THz waves have certain properties that allow them to penetrate through gas clouds much like light in the optical wavelength can go through a window, however they are blocked by thicker materials. This makes this frequency ideal for observing star formation where optical light is obscured by gas and dust, but THz waves can penetrate through to protostellar cores. THz waves can be observed using a heterodyne receiver as shown in Figure 1.

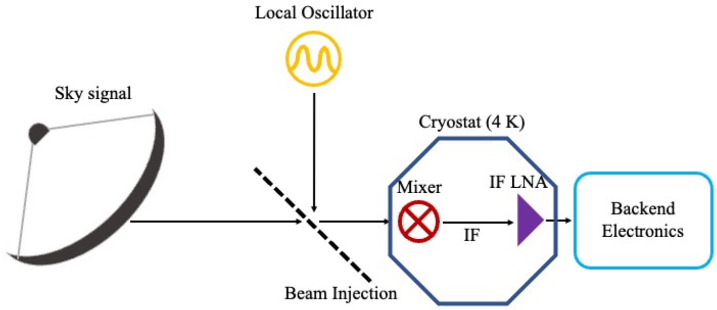

Figure 1: The current state-of-the-art heterodyne receiver for THz frequencies.

A heterodyne receiver mixes two signals of different frequencies and outputs their difference. The receiver is popular because phase coherence is maintained and thus the receiver can perform high spectral resolution spectroscopy.

The science goal of our project is to observe the formation of stars. Prior to birth, stars are formed from enormous clouds consisting of gas and dust, called Giant Molecular Clouds (GMCs). As gas and dust accumulate, the cloud becomes denser at its core, and gravity increases. The denser core, however, brings particles into closer contact, which creates more collisions and increases the cloud's temperature via friction between the atoms. Due to the principle of hydrostatic equilibrium, the cloud should find a balance between the forces of gravity and pressure (Shu 1982). For the cloud to continue its collapse, the cloud must emit heat to relieve the pressure. The heat is released through radiation from elements such as ionized nitrogen (N^+), ionized carbon (C^+), and neutral oxygen (O) (Hollenback and Tielens 1997; Seo et al. 2019).

Because these signals are small and are difficult to isolate it would be helpful to add an amplifier to the signal before it is mixed with the local oscillator. Currently there are no commercially available THz amplifiers and there are none that will amplify to the power needed to be useful in minimizing noise in the observations of gaseous regions of space.

This senior thesis builds on the senior design project lead by Kassidon Hatfield and Briston Bundy in mechanical and electrical engineering, respectively. In that project an experimental design was implemented to test a Quantum Cascade Meta-Surface Amplifier (QCMSA) to amplify frequencies in the 2.5-2.7 THz range. As part of the team, I traveled to the Jet Propulsion Laboratory (JPL) in June 2023 and tested the QCMSA using a frequency multiplier chain (FMC) as a source. After those tests, we decided to try a new type of source, a

Quantum Cascade Laser (QCL), which is the type of device on which the QCMSA is based. In order to use the QCL as a source, it had to be characterized. I traveled back to JPL during Spring Break 2024 to measure the QCL's I-V curve, frequency, and spot size.

Background on Quantum Cascade Lasers

A QCL is different from a conventional laser in several ways. A QCL uses multiple layers of semiconductor material, in our case it was gallium arsenide (GaAs), to create quantum wells (Williams, 2007). When extremely thin layers of this material (~ 1 nm) are electrically biased in a specific way, this produces a cascade of electrons that are only allowed to exist in small, allowed energy levels within the valance band. When the electron enters a quantum well in its excited energy state, a photon is released at a specific THz frequency as it undergoes an intersubband transition to a lower energy state (Williams, 2007). The electron then tunnels to the next quantum well that allows a lower energy level. The laser effect is achieved by having the atomic structure of the semiconductor material layered and electrically biased so that each quantum well has a lower energy level than the last and allows a photon to be released after the electron transitions to the lower energy level within the quantum well. This cascade is depicted in Figure 2 (Williams, 2007). This design amplifies the THz wave as it exits the QCL as a coherent THz source.

There must be extremely specific conditions for this lasing effect to be achieved. QCLs are very heat sensitive and do not work at room temperature. They must be cooled using liquid nitrogen and cannot output a continuous beam or they will overheat and the properties of the material that are being exploited to create the thin energy bands within the quantum wells will be lost. To work at a high-power output the QCL must be pulsed to ensure the semiconductor material stays cool enough to continue working properly (Williams, 2007; Curwen, 2022).

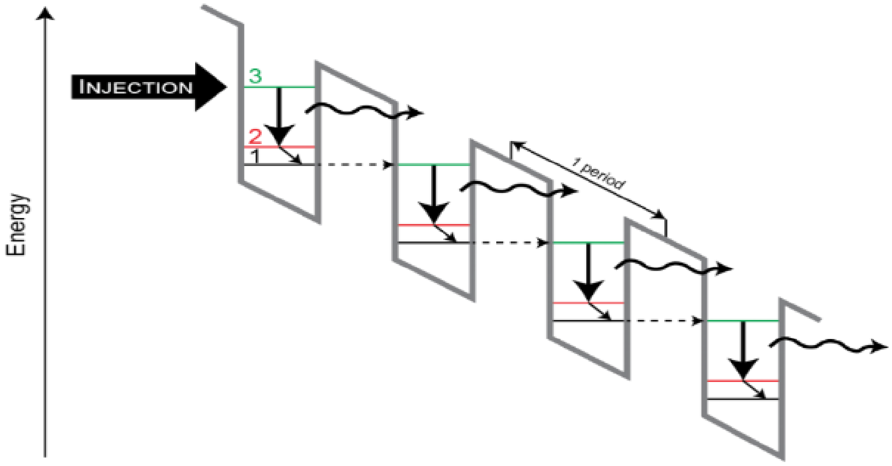

Figure 2. QCL energy diagram. The electron enters the first well in the top left in an excited state at line 3. The arrow from like 3 to line 2 shows the transition of the electron to a lower energy level. As this electron transitions, it also releases a THz wave. The electron then goes to the lowest allowed energy level as shown by the arrow from line 2 to line 1. The electron then tunnels into the next quantum well, entering in an excited state, and repeats this process as it cascades through the quantum wells.

II. Measurements

A. Experiment 1 summer 2023

The first experiment conducted in the summer of 2023 used a frequency multiplier chain (FMC) as a THz source for the amplifier tests. The FMC achieves an emission of a THz beam by utilizing Schottky Diode multipliers. A schematic of a FMC is shown in Figure 3. An input wave of ~100 GHz is amplified and then divided 4 ways. The signal of each branch is tripled and then recombined into two stages. Each of those two stages is tripled and then recombined for the final tripler achieving an output frequency 2700 GHz, or 2.7 THz (Maestrini, 2011). The reason for the power splits and recombination is due to the amount of power the triplers can accommodate before they are saturated. Without these stages, the power output would be much lower. This source was originally chosen because it can operate at room temperature and had a predictable gaussian beam pattern.

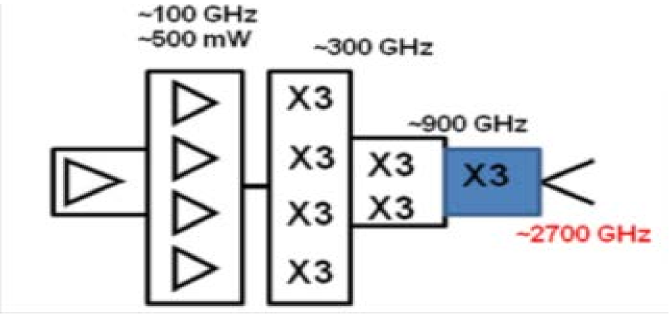

Figure 3. This is a diagram of the design of the FMC. This design takes 4 sources at ~100GHz and multiplies the frequency while combining the power of the 4 to reach one emitter of ~2700 GHz, or ~2.7 THz (Maestrini, 2011).

The downside of an FMC is that it provides a much lower power output than other potential sources such as a QCL. The power is frequency dependent as seen in Figure 4, but never exceeds 0.025 mW. The power measurements were taken using a lock-in amplifier to record the data. The lock-in amplifier is able to filter out the noise in the room giving a relative power of the FMC.

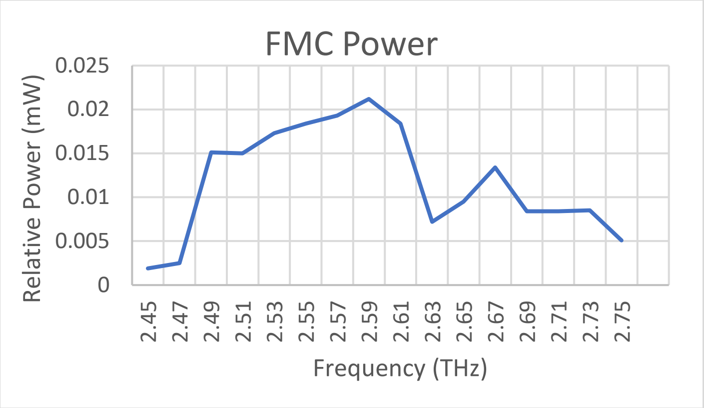

Figure 4. This is a measure of the absolute power of the FMC in a frequency sweep from 2.45 to 2.75 THz that was obtained during the summer of 2023 using the lock-in amplifier.

The lower power highly influenced the optical designs of the testbed. Lenses add loss to the system, so instead elliptical mirrors were chosen to direct and focus the beam. Elliptical mirrors are not frequency dependent and have two focal lengths, one at each foci making them the ideal choice for this project. Since the FMC has a beam radius of 0.242 mm and the desired size of the beam on the amplifier was under ~0.7 mm, the elliptical mirror block was designed for a magnification of 1.65x by making the focal lengths of the ellipse 16.5 cm and 10 cm. The mirror block was also designed to focus and reflect the beam in a way that allowed the angle of reflection to be as close to normal to the QCMSA as possible without the entering and exit beams interfering. On the other hand, it was feared that any angle of incidence larger that 10° would turn the waveguide ridges on the meta-surface into a diffraction grating (Curwen, 2022). A diagram is shown of the experimental setup is in Figure 5a.

Only a small area could be electrically biased for amplification. The properties of the meta-surface are such that any region of the QCMSA that was not biased would absorb the part of the THz beam that did not hit the biased area. This means the beam must be focused to the biased region. Although it is possible to manufacture a larger meta-surface, biasing it is too large of a challenge to overcome because the heat load of the amplifier would exceed the cooling capacity of the Stirling cooler. Thus, the size of the amplifying area has a limit of ~1mm.

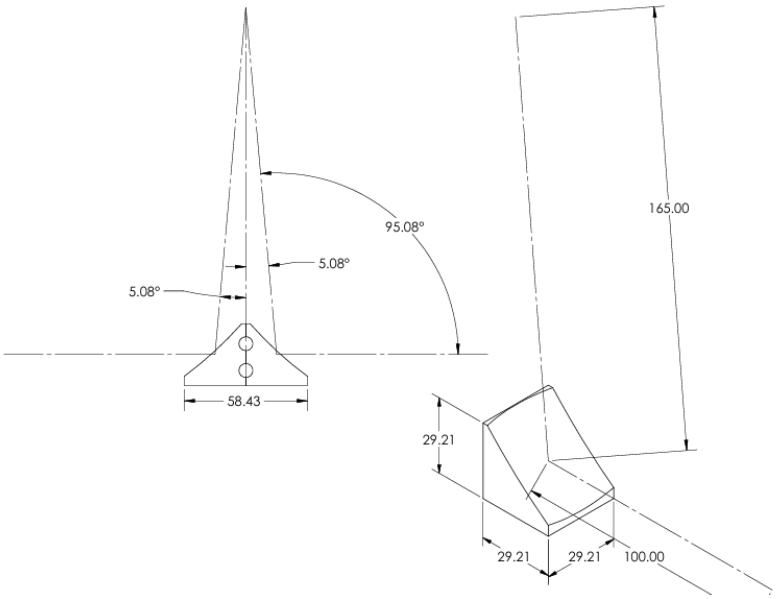

Figure 5a shows the mirror block design that was used in the optical testbed.

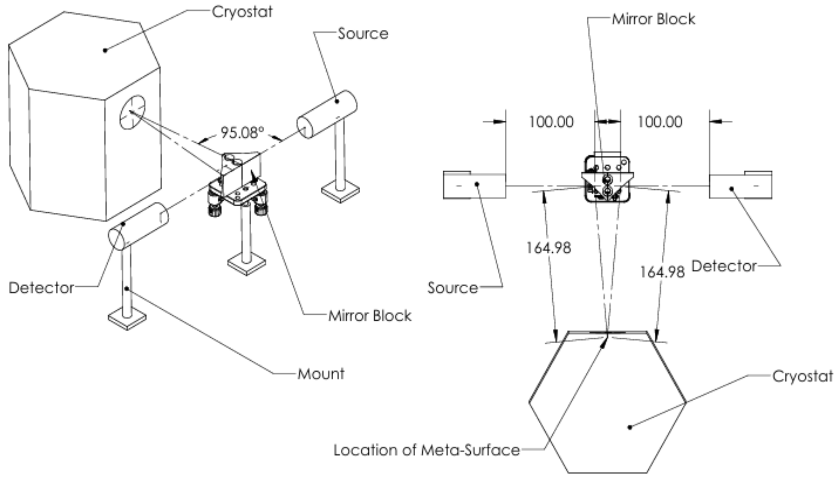

Figure 5b. shows the full design of the optical testbed that was used.

The optical testbed was setup as shown in the design pictured in Figure 5b, with the FMC as the source placed 10 cm away from the mirror block. The QCMSA was placed 16.5 cm away from the mirror's central axis and the detector was placed on the opposite side from the source 10 cm from the elliptical mirror block. The QCMSA was placed in a Stirling cooler. In order to achieve a low temperature, the QCMSA chamber was placed under a vacuum. Several frequency sweeps were taken with the bias voltage on the meta-surface at 3 V and 5 V. For the frequency sweep, we measured the output of the FMC in a range from 2.45-2.75 THz after being reflected onto the QCMSA, with measurements taken every .005 THz. The power measurements were taken using a lock-in amplifier, which removes the background noise, giving a differential measurement of the power. A higher bias voltage on the QCMSA resulted in better results. The most amplification was 5.8 dB, which was achieved at 2.48 THz. The graphs of the gain are pictured below in Figures 6.

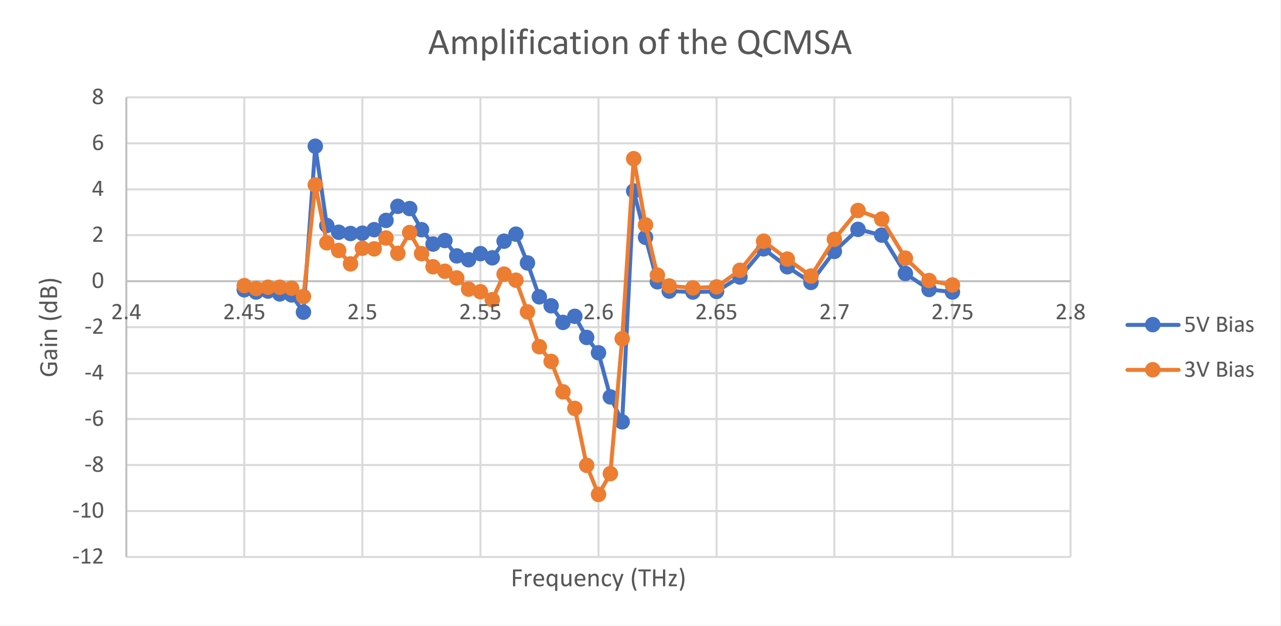

Figure 6. This graph shows the gain measured in dB of the THz signal after being reflected onto the QCMSA and then into the detector.

The conclusion reached from the data gathered in the summer of 2023 was that the beam size was too large when it reached the meta-surface. This caused an absorption in the power of the beam for the outer area and meant that although amplification was happening for the biased area of the meta surface, some of the beam was being absorbed. This led to a peak amplification of only 5.8 dB, when the theorized amount was up to 30 dB of gain. Figure 7 of the beam on the meta-surface is below and illustrates the problem when the beam diameter is greater than the amplification area.

Figure 7: The presumed problem with the amplifier is that the source over-illuminated the QCMSA biased region and thus part of the beam was absorbed (adapted from Curwen, 2022).

B. Experiment 2: Characterizing the QCL as a THz Source spring 2024

In the spring of 2024, the team at USI returned to JPL again to characterize a QCL developed by Dr. Chris Curwen that would be the new source of the amplifier tests to be conducted in the summer of 2024. To characterize the QCL, experiments were done to measure the IV curve, the frequency output, and the beam size. Since the expected beam of the QCL is 0.7 mm, a new mirror block was also designed and fabricated. This mirror block had focal lengths of 7.5 cm and 7.5 cm, giving a magnification of 1x.

To prepare for the measurement of the IV curve, the QCL was cooled to 77 K with liquid nitrogen. To ensure the system was working properly, we first measured the IV curve of a 50 Ω resistor. The QCL, to avoid overheating, which would stop the lasing effect, had to be pulsed on and off to keep the heat to a minimum for both the QCL and the QCMSA. A reference frequency of 30 Hz was used and then sent to the pulser firing at 10 KHz for the QCL. To ensure that data was only being recorded while the QCL was active, a device called a boxcar was used to sync the frequencies of the pulser and a second boxcar. The second boxcar was recording only while the IV curve only while the pulser was activating the QCL. A block diagram of the setup, the recorded IV curve, and the power curve can be seen in Figure 8a-c, respectively.

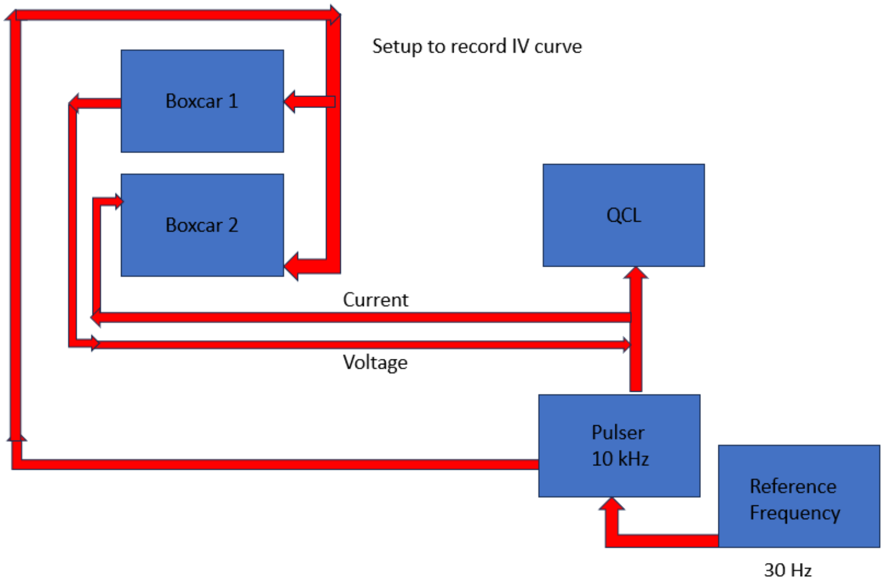

Figure 8a shows the block diagram of the IV curve measurement setup.

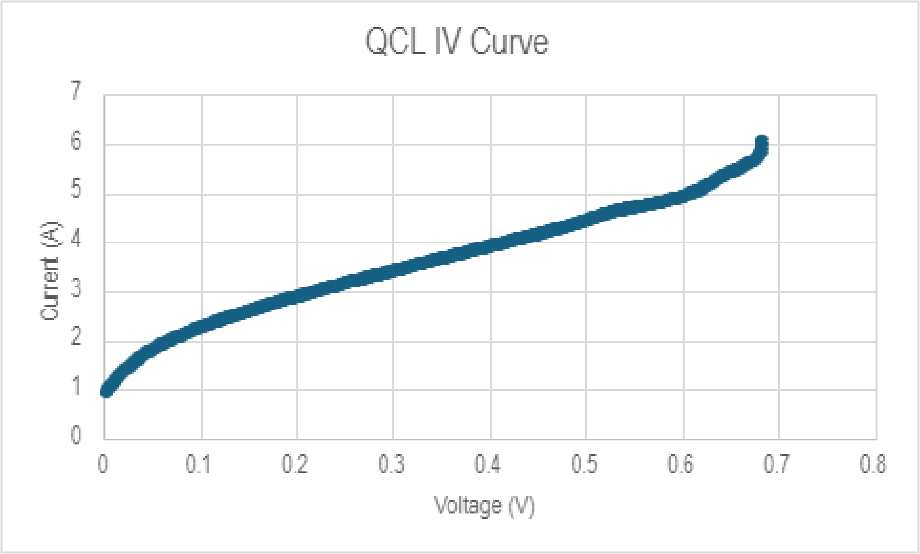

Figure 8b shows the IV curve recorded for the QCL.

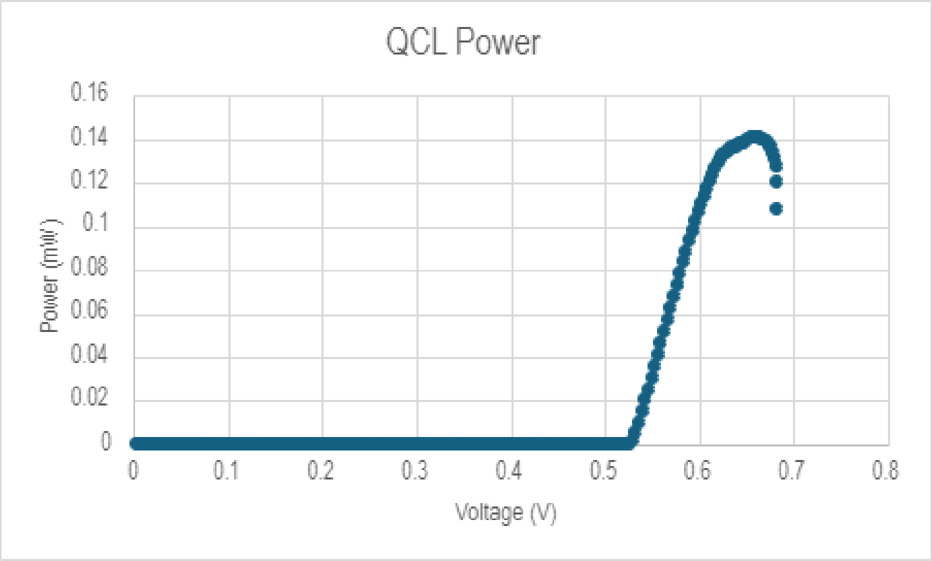

Figure 8c shows the power consumption of the QCL. This not the same as the power output.

The frequency output of the QCL was measured using a Michaelson interferometer. The way this device works is by sending the laser into a beam splitter and with multiple mirrors and a detector configured as is shown in Figure 9a. The distance of one of the mirrors is varied, which varies the path length of the reflected light. The wave constructively and destructively interferes with itself based on with it is in phase or out of phase with the part of the beam reflecting off of the stationary mirror. The exact frequency of the THz wave can be determined via a Fourier transform of the interference pattern. The data recorded from the frequency graph is presented in Figure 9b and shows the laser output 5.71835x mW at 2.73807 THz.

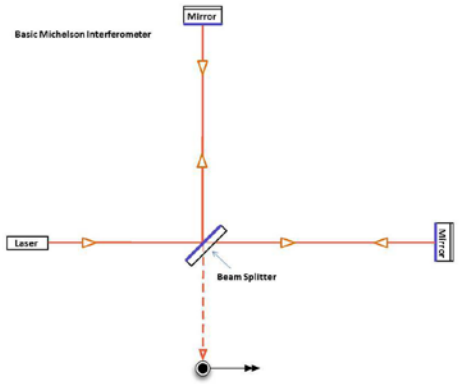

Figure 9a shows the Michaelson interferometer design.

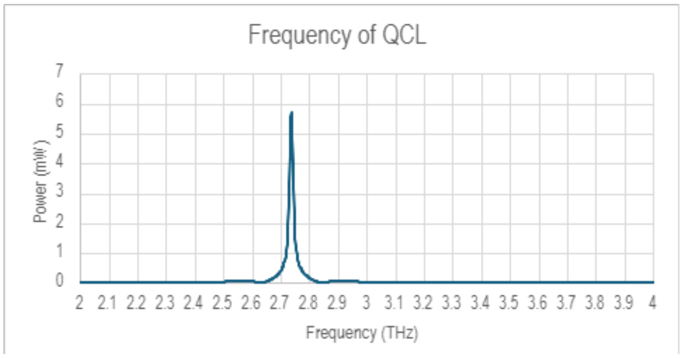

Figure 9b shows the Frequency output of the QCL.

After taking the frequency, power data, and finding the IV curve of the QCL, the next step was to determine the spot size. This was done with the elliptical mirrors as well as lenses. The QCL was pointed directly into the detector, which was a micro-bolometer pictured below in figure 10, to determine the maximum power. The first test was done with the original elliptical mirror where the QCL placed at the 10 cm focal length and the detector at 16.5 cm. An aperture was placed in front of the detector and the size of the hole was reduced until power was lost. To ensure that we were centered on the beam, the aperture's placement was changed, and the hole's size was reduced until the detector was reading maximum power while achieving the minimum size of the aperture hole. Using this method, the spot size at the focus was measured to have a

1.85 mm radius. Working backwards with a magnification of ~1.7x, the size of the beam leaving the QCL was calculated to be ~1.1 mm.

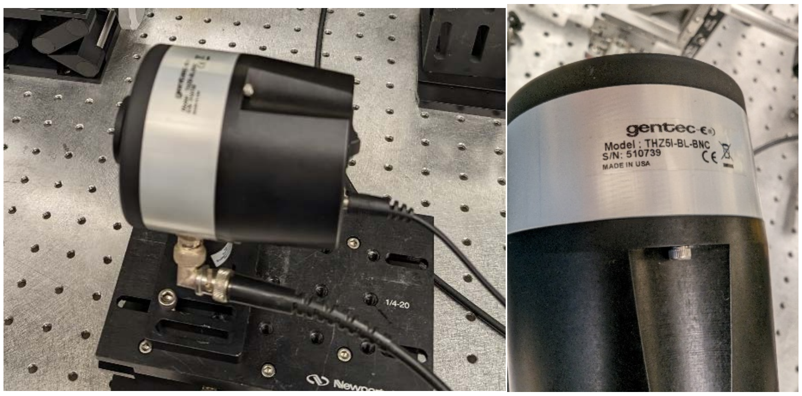

Figure 10. This is the micro-bolometer used as the detector in the tests done with the QCL.

The next alignment test was performed using the same method used in the above paragraph. Using the new elliptical mirror with focal lengths of 7.5 cm and a magnification of 1x, the beam size at the focus was measured to be 1.1 mm in radius. This test determined that when using the elliptical mirrors, the spot size of the beam from the QCL was not reduced enough to avoid the absorption properties from the non-biased region of the metasurface.

Since the QCL is over 100x more powerful than the FMC, this allows the use of lenses in the design as a loss of power is not as detrimental since the full power of the beam can still be distinguished from noise by the detector. JPL was able to provide a box of lenses, but their focal lengths were unknown. The focal lengths of the lenses were found by using the aperture to find the focus and measuring the each of the distances between the QCL and the lens and the aperture to the lens. After testing several lenses, using the right combination of distances and lens focal length, a beam size of 0.8 mm for the QCL was achieved. This was done using a lens with focal length of 6 cm and 8 cm and a magnification of 3/4x.

III. Summary, Discussion, Conclusions, and Future Work

After the results of the first experiments in the summer of 2023, the main problem with reaching higher amplification was the spot size at the QCMSA was too large and some of the beam was being absorbed instead of amplified. This experiment still yielded a net amplification of over 5 dB at its highest peak. The problem of spot size was solved using lenses with the QCL as the source. Since there was more power available using the QCL as a source, loss through lenses was not as detrimental to the detection of amplification, this allowed the use of lenses in the optical testbed. A spot size of less than 1 mm was achieved using lenses, allowing the full beam to be contained within the amplifying region of the QCMSA.

The next step of this project is going to take place in May of 2024 and will utilize lenses as a focusing element. Lenses are being ordered and will be provided by JPL while the team at USI will design a device to hold and angle flat mirrors. The design of the testbed will contain 2 lenses with the QCL and the QCMSA at the focus of the first lens and the second lens will be placed in the beam path after being reflected off the QCMSA and the flat mirror to focus the beam into the detector. This design will theoretically focus the beam to less than 1 mm at the QCMSA and focus the beam into the detector.

The final plan for this amplifier is to place it in a heterodyne receiver system and use it to amplify terahertz signals received by radio telescopes. By placing the QCMSA in the beginning of the system as shown in Figure 11, this will increase the signal to the mixer and improve the overall receiver sensitivity.

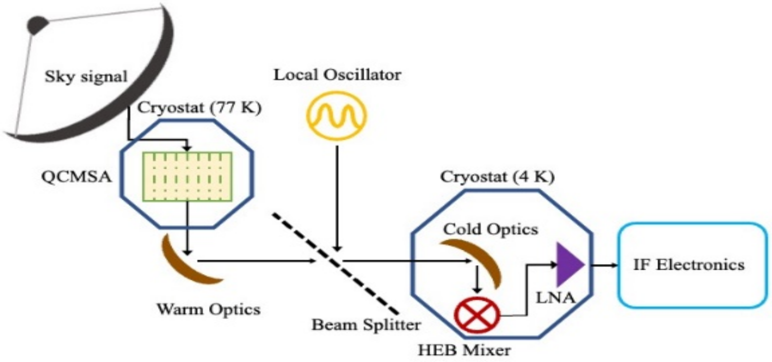

Figure 11 shows the configuration of a heterodyne receiver system with a QCMSA installed at the beginning.

If the amplification test is successful, the next step of the project will be to place the design in a heterodyne receiver and measure the improved sensitivity. Lastly, the amplifier could fly on a high-altitude balloon to allow the system to get above the atmosphere and record data where there is little water to absorb the THz frequencies. If this test is successful, the design will be a huge advance to closing the THz gap in existing amplifiers and will allow the observation of star forming regions in GMCs to take place at a much higher sensitivity level.

IV. Appendix I: Mirror Polishing

The mirrors were machined at the University of Southern Indiana's Applied Engineering Center. After they were made, the team at USI hand polished the mirrors up to 15,000 grit sandpaper. After the sanding was completed, aluminum polish was applied to the mirrors. The main purpose of sanding the mirrors was to test their alignment and focusing with a laser in the optical wavelength. The mirrors were already smooth enough without any sanding, since we were using them for THz waves, the rough surface would not matter at those wavelengths. A picture of the mirror after polishing can be seen in the figure below.


Figure 12. This figure shows the polished mirror.

V. Acknowledgements

This project was a collaboration between the University of Southern Indiana and NASA's Jet Propulsion Laboratory. I would like to thank Dr. Jon Kawamura and Dr. Chris Curwen for inviting us to their lab and allowing us to be a part of this project. I would also like to thank the student team at USI, Kassidon Hatfield, Briston Bundy, Derrick Thompson, Melanie Cedeno, Miguel Pinto, Noah Geisler, and Landon Gates. It was a great experience to work with these engineers. I would also like to thank my family and my fiancé for their support throughout this entire project. My greatest thanks go to the faculty member at USI who allowed me to be a part of this endeavor and is the reason all of the students at USI got to participate in cutting edge research, Dr. Jenna Kloosterman.

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