NDnano
Notre Dame Nanoscience and Technology

NDnano Summer Undergraduate Research 2023 Project Summary

1. Student name & home university: Jeffrey Yang, University of Notre Dame

2. ND faculty name & department: Dr. Gergo Szakmany, Electrical Engineering

3. Summer project title: High Frequency Response of Thermoelectrically Coupled Nanoantennas

4. Briefly describe new skills you acquired during your summer research:

- How to set up and use an acousto-optic modulator for high optical frequency measurements.
- How to use the rest of the TECNA measurement setup, including the CO_2 laser, waveplates (half-wave and quarter-wave), the vacuum chamber, and the lock-in amplifier.
- How to interpret and clearly present data to my research group and to my peers.
- How to read and understand academic journal papers relating to my research.

5. Briefly share a practical application/end use of your research:
TECNAs are wavelength- and polarization- selective long-wave infrared detectors that can be used for thermal imaging. It is industry standard to vacuum package uncooled thermal detectors. To this end, my research characterizes the gain and speed of TECNAs as a function of vacuum pressure.

6. 50- to 75-word abstract of your project:
This work investigates the frequency response of dipole and spiral thermoelectrically coupled nanoantennas (TECNAs) in vacuum. TECNAs are polarization- and wavelength-selective long-wave infrared (LWIR) detectors. Theory predicts that in vacuum, TECNA responsivity increases, while speed decreases. An acousto-optic modulator (AOM) is used to modulate the optical input signal to frequencies up to 100 kHz. Measurements of dipole and spiral TECNAs match theory. In addition, the extinction ratio of spiral TECNAs is found to be lower in vacuum.

7. References for papers, posters, or presentations of your research:
Poster:
Yang, J. Z., Szakmany, G. P., Bernstein, G. H., Orlov, A. O., Kinzel, E. C., Aquino, H. R. O., Porod, W., Finnan, C. P., Strobel, D. J., & White, S. M., "High Frequency Response of Thermoelectrically Coupled Nanoantennas," [Poster Presentation], ND Research Symposium, Notre Dame, IN, (2023).

Reference materials:
[1] Graf, A., Arndt, M., Sauer, M., & Gerlach, G., "Review of micromachined thermopiles for infrared detection," *Meas. Sci. Technol.* **18**, 8, doi: 10.1088/0957-0233/18/7/R01 (2007).
[2] Finnan, C. P., Kinzel, E. C., Szakmany, G. P., Orlov, A. O., Aquino, H. R. O., Porod, W., & Bernstein, G. H., "Low-Pressure Performance of Ultrafast, Nanoantenna-Based, Long-Wave Infrared Detectors," Under review (2023).
[3] Szakmany, G. P., Orlov, A. O., Bernstein, G. H., Porod, W., "Response increase of antenna-coupled nanothermocouples by thermal insulation," *Journal of Vacuum Science & Technology B* 36, 052203. https://doi.org/10.1116/1.5044534 (2018).

One-page project summary that describes problem, project goal and your activities / results:

In a thermoelectrically coupled nanoantenna (TECNA), a resonant antenna excited by long-wave infrared radiation (LWIR) heats the hot junction of a nanoscale thermocouple (NTC) via joule heating. The resulting signal measured between the hot and cold junctions of the NTC is a voltage that is proportional to the temperature difference, which corresponds to the intensity of the optical excitation. The antenna nature allows for TECNAs to be designed to detect infrared radiation over a narrow range of wavelengths and polarizations. In vacuum, heat loss due to air decreases, resulting in an increased TECNA response and a longer thermal time constant. Therefore, in vacuum, responsivity should improve, and device response cutoff frequency should decrease. Previous research has already shown that, in vacuum, dipole TECNA responsivity improves significantly, and that dipole TECNA frequency response is flat up to 10 kHz [2]. The main objective of this project was to characterize the frequency-dependent response of dipole and spiral TECNAs in vacuum and at atmospheric pressures to determine the TECNA response cutoff frequency.

I spent the first few weeks setting up an acousto-optic modulator (AOM) to replace the mechanical chopper, which increased the measurement bandwidth from 10 kHz to 100 kHz. The frequency response of the TECNAs is determined by sweeping the frequency of an input optical square-wave signal and measuring the output voltage. The AOM is used to create the square-wave input. In an AOM, a standing acoustic wave in an optically transparent material (in this case, Germanium) creates a diffraction grating, allowing for Bragg diffraction. Modulating the acoustic wave with a square wave results in a square-wave modulation of the diffraction orders of the beam. By adjusting the incident angle of the beam to the AOM and the power of the acoustic wave, the diffraction efficiency of the AOM can be maximized. An IR lens was used to focus the beam at the AOM to increase the modulation depth. Another IR lens behind the AOM was used to recollimate the first diffraction order. A position-adjustable gold-plated mirror was used to redirect the beam through a ZnSe window and onto the TECNAs inside the vacuum chamber. Through precise positional adjustment of measurement equipment (see Figure 1), the first diffraction order was aligned to the TECNAs, and the irradiance and modulation depth were maximized.

In order to minimize the measurement error, I replaced the previously used 12.6 kHz bandwidth pre-amplifier with a 5 MHz bandwidth pre-amplifier. The frequency-dependent gain of the new pre-amplifier was characterized up to 100 kHz, and all subsequent frequency measurements were normalized to this gain characteristic. I also observed some frequency-dependent electrical pickup; when the beam was blocked, an output voltage of up to 14 µV was measured, which would significantly impact the high-frequency output signals (which are on the scale of tens of microvolts). After adjusting the position and length of wire connections and replacing a signal generator, the electrical pickup noise was reduced to ~0.3 µV.

After addressing the measurement error, I measured the frequency responses of dipole TECNA arrays at both vacuum (1 mTorr) and atmospheric pressures. Measurements showed that while responsivity improves significantly in vacuum (by 3x-5x), cutoff frequencies in vacuum (20-35 kHz) are consistently lower than those at atmospheric pressures (35-45 kHz), which is in agreement with theory. However, we also observed a low frequency roll-off that could not be explained by the amplifier characteristic. From a thermal perspective, the frequency response of a TECNA begins to roll-off with increasing frequency because the TECNAs cannot heat or cool to an equilibrium state before the optical input signal changes, resulting in a lower measured voltage. Therefore, the low-frequency roll-off of the measured frequency response could not be attributed to thermal behavior of the TECNAs.

The frequency response of singular spiral TECNAs at both vacuum and atmospheric pressures were measured. Spiral antennas resonantly absorb circularly polarized light of a specific rotation or handedness. The selectivity of polarization response is called the extinction ratio. For singular spiral TECNAs excited by circularly polarized light of matching handedness, measurements showed that while responsivity improves significantly in vacuum (by ~2.8x), measured cutoff frequencies in vacuum (~16 kHz) are consistently lower than those at atmospheric pressures (~38 kHz), which is in agreement with theory. Unlike the arrays of dipole TECNAs, the frequency response of single spiral TECNAs was measured to be flat, even to the lowest measured frequencies.

The frequency response of the spiral TECNAs excited by circularly polarized light of non-matching handedness was also measured and was used to calculate the extinction ratio. The measured extinction ratio in vacuum (~4.5x) is lower than in atmosphere (~8x) but is still large enough that spiral TECNAs can differentiate between right-handed and left-handed circularly polarized light.

Investigations to be conducted include increasing the bandwidth of the measurement setup to measure the full frequency response of the TECNAs in vacuum and at atmosphere and determining the thermal behavior of spiral TECNAs through simulation and further experimentation. The goal is to use this work and future work next semester in a paper detailing spiral TECNA thermal behavior.

Figure 1. Acousto-optic Modulator Positioned in the Measurement Setup