Rapid infrared imaging with silicon-based cameras

Purpose: Infrared (IR) imaging is important for a myriad of applications, including biomedical imaging, surveillance and remote sensing. Traditionally, IR is done with dedicated IR cameras, but such devices suffer from high thermal noise, low pixel numbers, as well as low affordability. In this proposal, I will work on a new infrared imaging technique that overcomes these limitations. Instead of using an IR camera, I will use a regular silicon-based camera to detect IR photons through the mechanism of non-degenerate two-photon absorption (NTA). The infrared imaging set-up is shown in Figure 1. Although our research group has demonstrated NTA-based IR imaging before[1], I will be the first to use this mechanism with the principle of hyper-spectral imaging, whereby each pixel in the image represents an IR spectrum. I aim to demonstrate this principle and utilize it to generate high-definition, chemically selective images of phase segregated polymer samples.

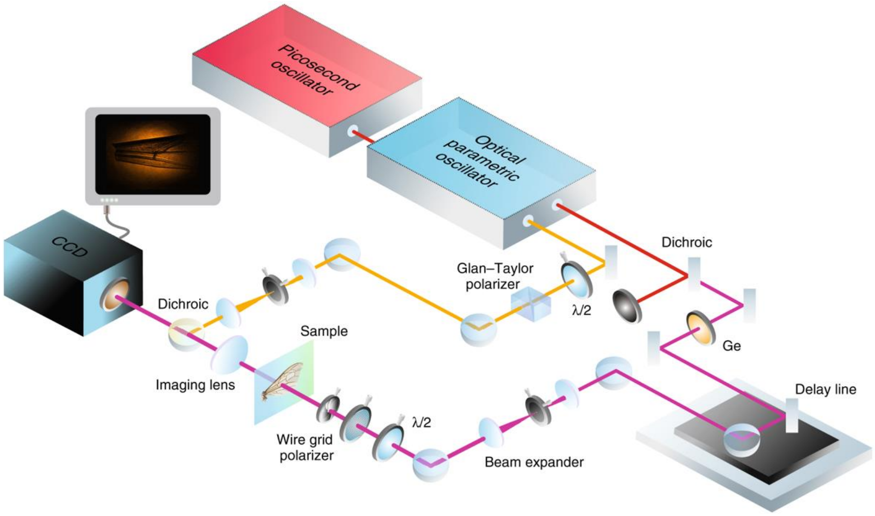

Figure 1. Infrared imaging system in a Si-based CCD camera using non-degenerate two-photon absorption.

Background and motivation: Characteristic molecular vibrations have their resonance frequencies in the IR range of the electromagnetic spectrum. Therefore, the IR range is important for chemically selective imaging applications, whereby the image contains contrast derived from the spectroscopic properties of molecules in the sample. IR imaging is critical for biomedical imaging applications, making it possible to visualize tissue samples based on their molecular content. IR mapping is also important for imaging novel materials, including films made from polymer blends.

Despite the strong attributes of the IR imaging technique, it suffers from several shortcomings. Among these is the lack of a high-definition IR camera. Existing IR cameras not only suffer from high thermal noise, but the number of pixels in their displays is also too low for demanding imaging applications. This is a technological hurdle that has stifled progress in the field of IR imaging. To overcome this hurdle, our group has developed an alternative detection method for IR photons that uses silicon-based cameras instead. In this method, the IR photon on the silicon chip coincides with another photon from a gate beam, such that the combined photon energy of the two photons is sufficient to bridge the bandgap of silicon.[1, 2] This process is called non-degenerate two-photon absorption (NTA). Because modern day silicon chips feature megapixel displays, NTA-based IR imaging makes it possible to rapidly produce high-definition images. In addition, Si-based cameras are intrinsically low noise and are significantly more affordable. Our group has demonstrated high-definition IR imaging with NTA up to frame rates of 500 fps.[3]

The next step in this development is to use NTA-based IR imaging for generating so-called hyper-spectral maps. Our group has taken some preliminary hyperspectral images (Figure 2). This means that each pixel in the image contains spectral information. From this information, the chemical identity of the material at the pixel location can be derived, thus allowing chemically selective imaging. This capability is important for rapid chemical imaging of a variety of samples, including layer materials made from polymer blends.

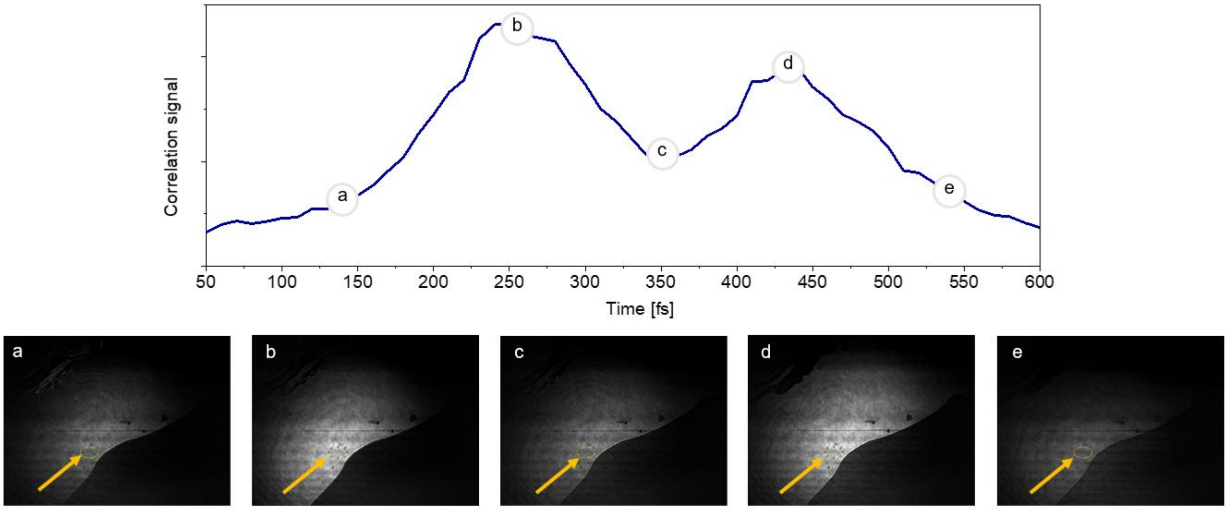

Figure 2. Preliminary hyperspectral images of vacuum grease. The spectrum shows a change in absorption by stepping over the pulse in time. The lettered figures are images at specific times during the pulse, with the targeted area shown with the yellow arrow.

<u>Research strategy</u>: The main goal of this research is to develop a spectral scanning method for NTA-based IR imaging. Two criteria have to be met: 1) high spectral resolution and 2) rapid spectral scanning capability. I will achieve this by implementing the principle of ‘spectral slicing’. For this purpose, I will use a broadband IR laser pulse, and I will use a high dispersive material to ‘stretch’ the pulse in time. By doing so, the different colors of pulse will arrive at the camera chip at different times. By using a short gate pulse, only a narrowband portion of the IR pulse will be probed through the NTA process, thus allowing imaging with high spectral resolution. In addition, by rapidly scanning the time delay between the IR and gate pulse, I will be able to spectrally sweep the detection window. The result is a very fast spectral imaging method.

Timeline and responsibilities: To achieve these goals, I will work closely with a graduate student [Redacted] and with the supervision of our group’s principal investigator [Redacted]. I will pursue the following steps for my UROP project:

Fall 2022: Weeks 1-3

- *Prepare polymer blend samples*. I have chosen to work with a blend of polystyrene (PS) and polymethyl methacrylate (PMMA). These polymers have different IR absorption spectra and can be discriminated by their IR spectral features. I will create films by melting the materials in controlled fashion with a hot plate. I will acquire IR absorption spectra from the films using a FTIR spectrometer equipped with a refractometer as well as using transmission. After spectral characterization, the samples will be subjected to NTA-based imaging studies.

Fall 2022: Weeks 4-10

- *Characterize the pulse chirp*. The spectral resolution depends on the degree of ‘chirp’ on the IR beam, which refers to the extent by which the different colors are time-stretched. Characterizing the chirp parameter is important for determining the spectral resolution. I will use pulse cross correlation measurements and spectral bandwidth measurements to characterize the spectral chirp. This work involves optical measurements as well as a quantitative analysis for extracting the desired parameters.

Winter 2023: Weeks 1-4

- *Perform the first spectrally-resolved NTA measurements*. I will work with the graduate student to record spectroscopically sensitive IR maps of the polymer samples. We will target the spectral 2700-3200 cm^{-1} range, which corresponds to the carbon-hydrogen vibrational stretching modes, as well as the 1200-1800 cm^{-1} range, which harbors the carbon-carbon stretches as well as various bending modes. I expect that this spectral analysis will allow me to discriminate the PS from the PMMA in the image.

Winter 2023: Weeks 5-10

- *Application of hyper-spectral NTA imaging to biological samples*. After demonstrating the principle of hyper-spectral NTA imaging on polymer samples, we will use the technique to map fixed tissue sections. The samples are obtained from a commercial data bank and consist of thinly sliced breast tissue sections. I will produce hyper-spectral IR images from this sections and compare the results with published data acquired with conventional (low definition) FTIR imaging techniques.

Proposed Budget:

Item	Budgeted Amount	Explanation and Justification for Expense
2 calcium fluoride windows	$262	The polymer samples are placed between windows for transmission FTIR measurements.
4 calcium fluoride coverslips	$240	The polymer samples are melted and blended on these coverslips.
2g of pure gold	$186	Gold is melted to make thin gold films for the FTIR refractometer measurements.
Sample holder	$180	To hold the samples in the FTIR compartment.
Poster	$50	For the UROP symposium poster session.
PMMA	$90	PMMA (polymethyl methacrylate) will be blended with PS for the first hyperspectral image sample.
PS	$70	PS (polystyrene) will be blended with PMMA for the first hyperspectral image sample.
Total Budget =	**$1,078**	

All additional materials, such as more gold, coverslips, or samples, will be covered with the additional funding up to $3,000 from the lab.

Conclusion. I expect that I can complete the proposed steps listed above within the duration of the UROP fellowship. The results of this research will be compiled in a manuscript that will be submitted to a peer reviewed scientific journal. I am very excited about this project as it allows me to use my skills as a spectroscopist and learn additional skills in optics, sample preparation, analysis and scientific communication.

References

1. Knez, D., Hanninen, A.M., Prince, R.C., Potma, E.O. & Fishman, D.A. Infrared chemical imaging through non-degenerate two-photon absorption in silicon-based cameras. *Light: Science & Applications* 9, 125 (2020).
2. Potma, E.O., Knez, D., Chen, Y., Davydova, Y., Durkin, A., Fast, A., Balu, M., Norton-Baker, B., Martin, R.W., Baldacchini, T. & Fishman, D.A. Rapid chemically selective 3D imaging in the mid-infrared. *Optica* 8, 995-1002 (2021).
3. Potma, E.O., Knez, D., Ettenberg, M., Wizeman, M., Nguyen, H., Sudol, T. & Fishman, D.A. High-speed 2D and 3D mid-IR imaging with an InGaAs camera. *APL Photonics* 6, 096108 (2021).