

# Exploration of Charge Dynamics of Well-Aligned CNT (6,5) Through THz Generation

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Homogenously aligned carbon nanotube (CNT) films are able to accentuate the unique anisotropic properties of individual CNT and allow for greater control of these qualities. Knowing these characteristics will help us understand more about the applications of homogenously aligned CNT films. This research will explore the charge dynamics of CNT. Using CNT in a photo-antenna, THz radiation was produced and detected through terahertz time-domain spectroscopy (THz-TDS). Variations included the polarization of the light falling on the sample, the alignment of the photoconductive antenna (PCA) with respect to the aligned CNT, and the voltage bias applied to the PCA. Further variation of the pump wavelength is expected to cause changes in the excitation and relaxation times of the CNT. This research allows for the exploration of the anisotropy of CNT, the efficiency of photon generation and generation of THz radiation, and the ease of breaking the electron-hole pairs in CNT.



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## Background

- Homogenously aligned carbon nanotube (CNT) films accentuate unique anisotropic properties of individual CNT and allow for greater control.
- THz radiation is generated using CNT (6,5) allowing for exploration of the charge dynamics and potential applications of homogenously aligned films.

## Introduction

- In this study, it was attempted to measure THz radiation from aligned CNT at various wavelengths and powers of the excitation laser to explore the charge dynamics of CNT
- THz radiation encompasses frequencies between 100 GHz and 30 THz
- Terahertz time-domain spectroscopy (THz-TDS) using photo-conductive antenna (PCA) can generate THz radiation and detect the amplitude and phase of the THz pulse [1].
- Absorbance ability of CNT (peaks corresponding to the E11, E22, and E33 locations within the conduction band) peaks around the IR, visible, and UV wavelengths [2].
- Exploration of wavelengths between 720 nm and 535 nm which will excite charge carriers to E22.

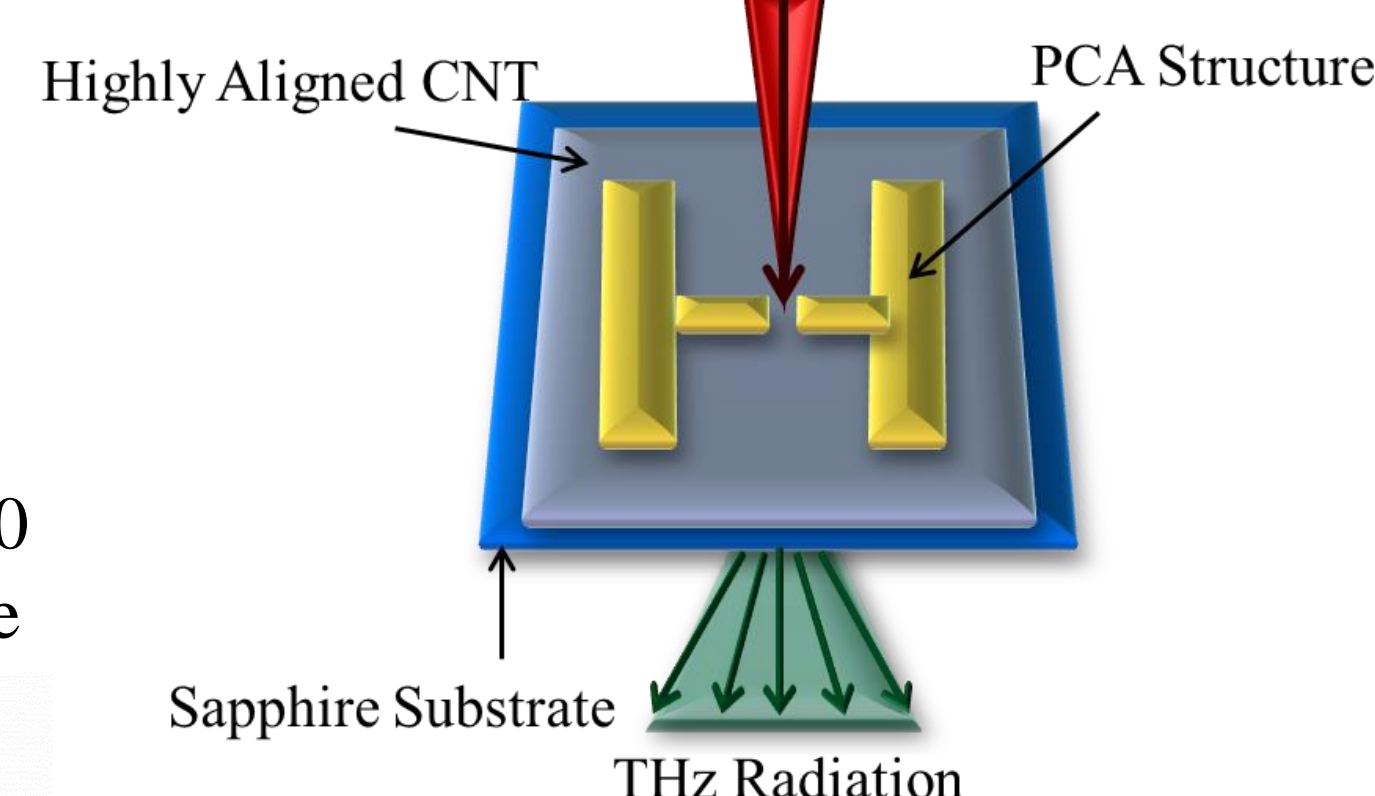


Fig. 1: Diagram of the PCA used as the "sample" to generate THz radiation.

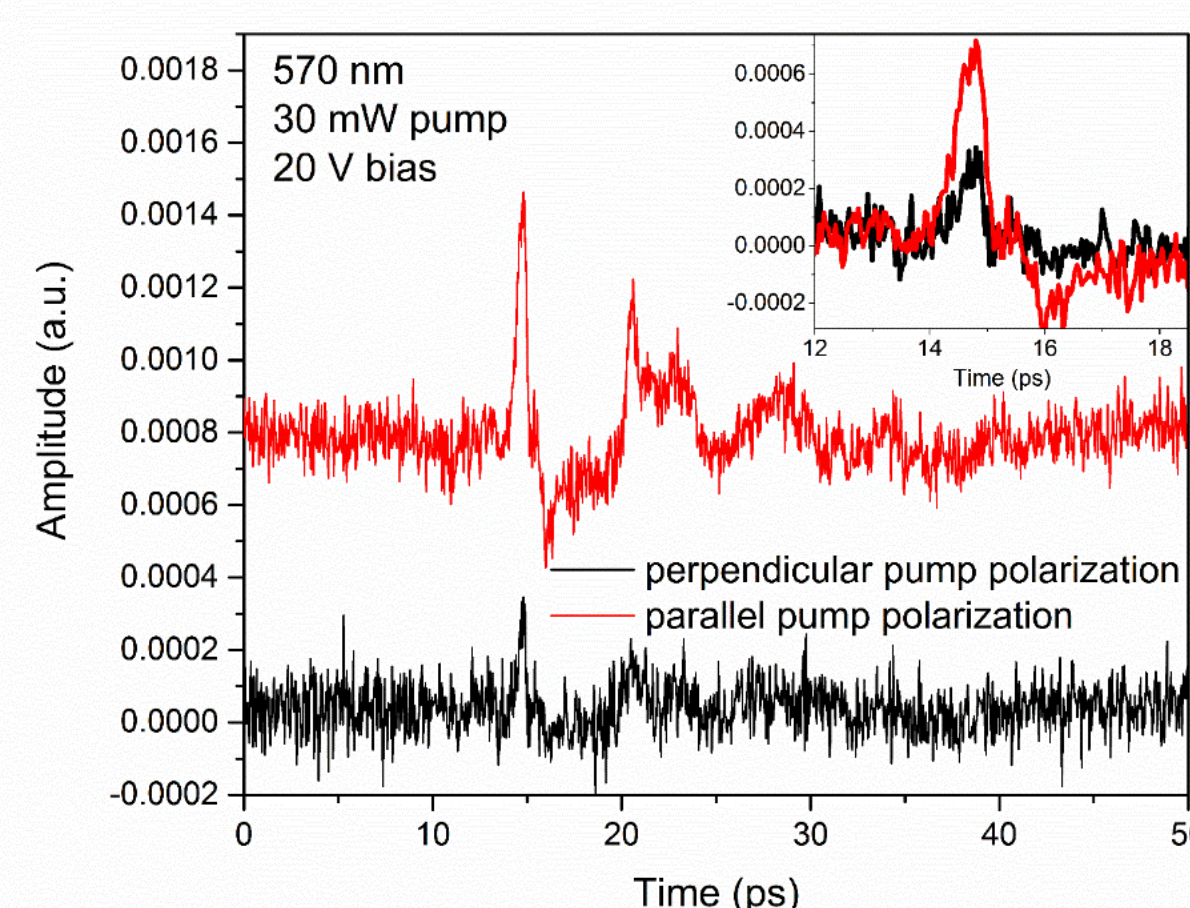


Fig. 2: Change in THz emission between perpendicular and parallel pump polarization with respect to the dipole. CNT sample was illuminated with pump beam of 570 nm wavelength at 8 mW with a bias voltage of 20 Volts.

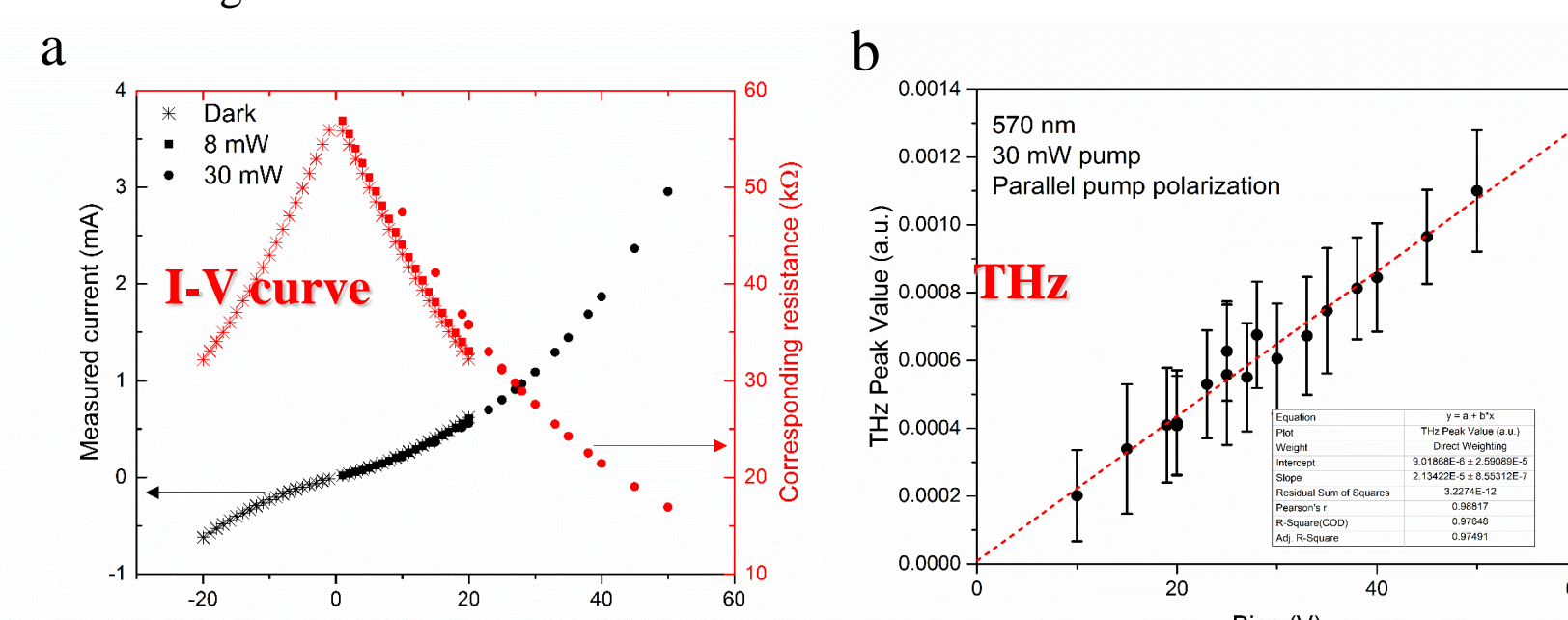


Fig. 3: a: I-V curve of the CNT sample utilizing voltages between -20 Volts and 50 Volts. b: Change in THz pulse peak with respect to voltage bias.

- Previous research utilizing a pump beam of wavelength 570 nm explored voltage bias effects on THz generation.
- Peak value of THz pulse measured with various bias voltages and I-V curve measured before illumination, at 8mW and at 30mW.
- Plot of THz peak voltage follows a linear path; the I-V curve measurements follow a nonlinear path.
- A diode barrier could be present between the contacts on the PCA. It was assumed there would be a minimum voltage bias to disassociate electron hole pairs [3] but low voltages are able to disassociate these pairs.

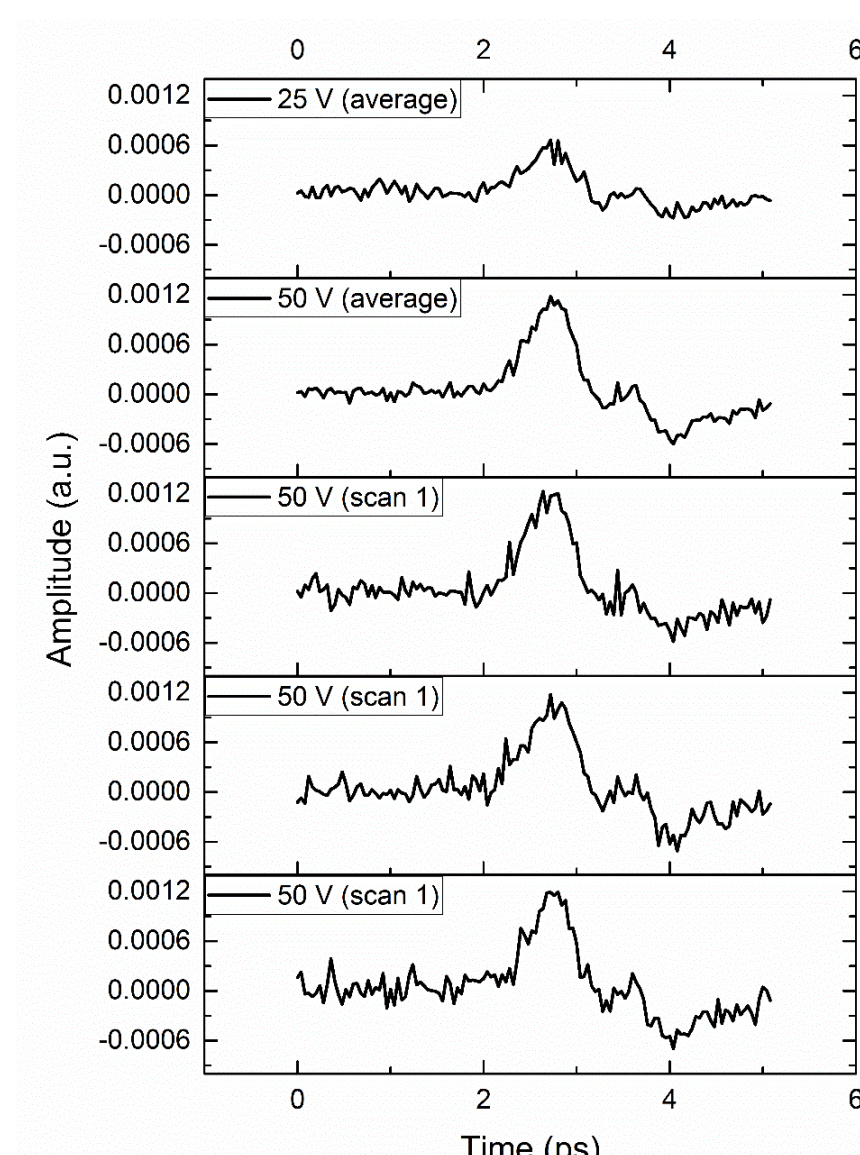


Fig. 4: One THz waveform shown for voltage bias of 25 Volts and four waveforms shown for voltage bias of 50 Volts.

## THz Generation Utilizing Normal THz-TDS

- Delay stage used to accommodate scan of full waveform
- Fourier Transform of the data is taken to determine frequencies present.

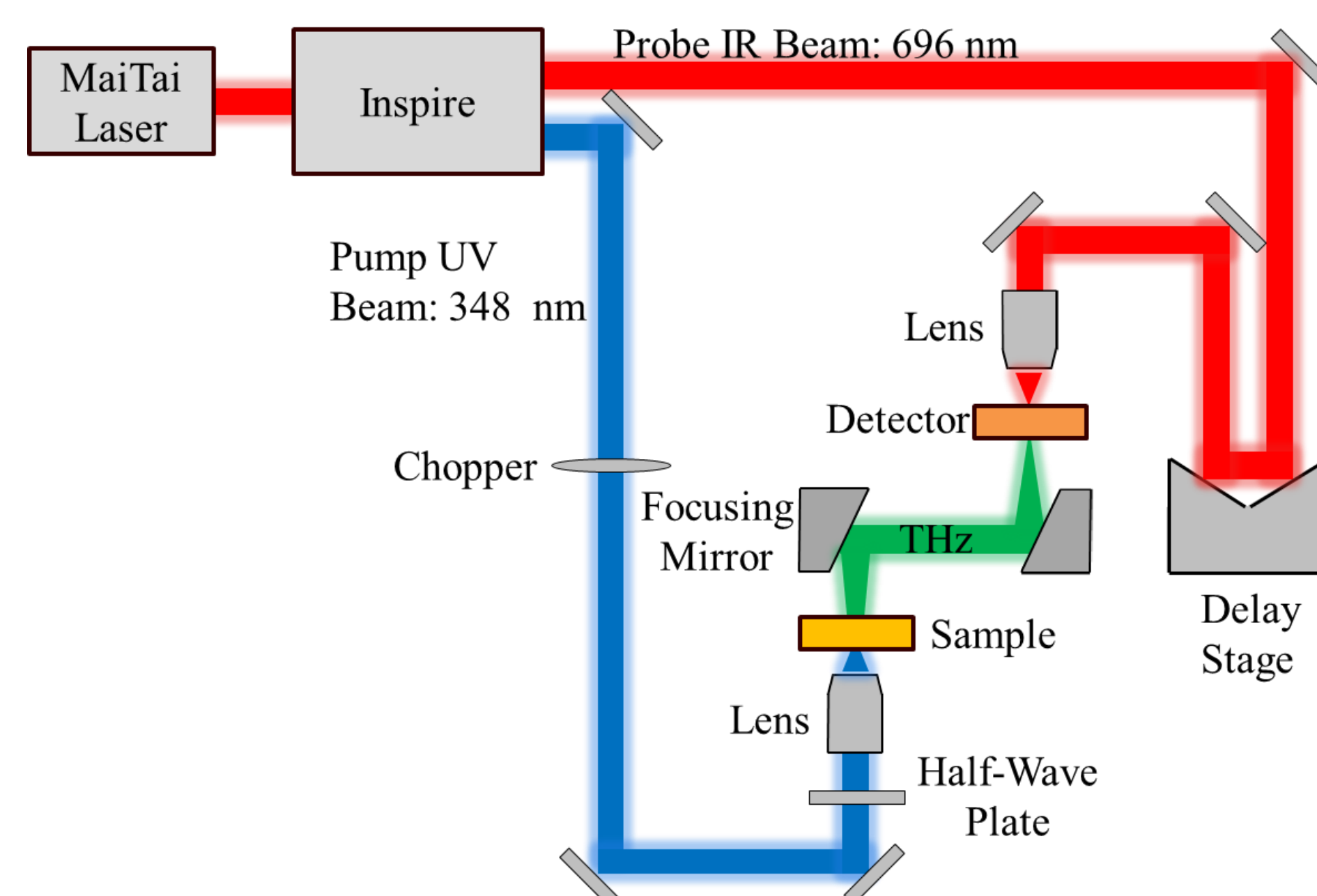


Fig. 5: Top view schematic of the experimental apparatus. A UV beam is used as a pump and is focused onto the sample to generate THz radiation. An IR beam is used as a probe and is reflected by a delay stage before being focused onto the detector.

- Variables to be explored:
  - Pump beam polarization
    - Adjusting the half-wave plate with respect to the dipole
  - Beam intensity
    - Adjusting to maximum intensity
  - Beam wavelength
    - Testing wavelengths between 720 nm and 540 nm
  - Applied voltage bias.
    - Adjusting between -50 and 50 volts

## THz Generation Using UV Radiation

- Inspire system damaged during routine maintenance.
- UV beam (348nm) substituted to excite the charge carriers in the sample.
  - CNT has a spectrum absorbance peak around 348nm (corresponding to E33) [2].
  - Reduction of the amplitude of the signals and higher wavelengths of THz are cut off were observed when system was optimized utilizing LT-GaAs in the PCA.
  - Possibly due to the mobility of the charge carriers being lower in the new band.

- When voltage bias was inverted or cut off (Fig. 6), no change resulted in THz radiation pattern, evidence that the CNT is not generating THz radiation.
- Substitute PCA not containing semiconductor material did generate THz radiation.
- Removing PCA from the holder, leaving only the silicon lens (which collimates the THz radiation), THz radiation could be generated.
- Resistance of the CNT sample increased four orders of magnitude when exposed to the UV beam.

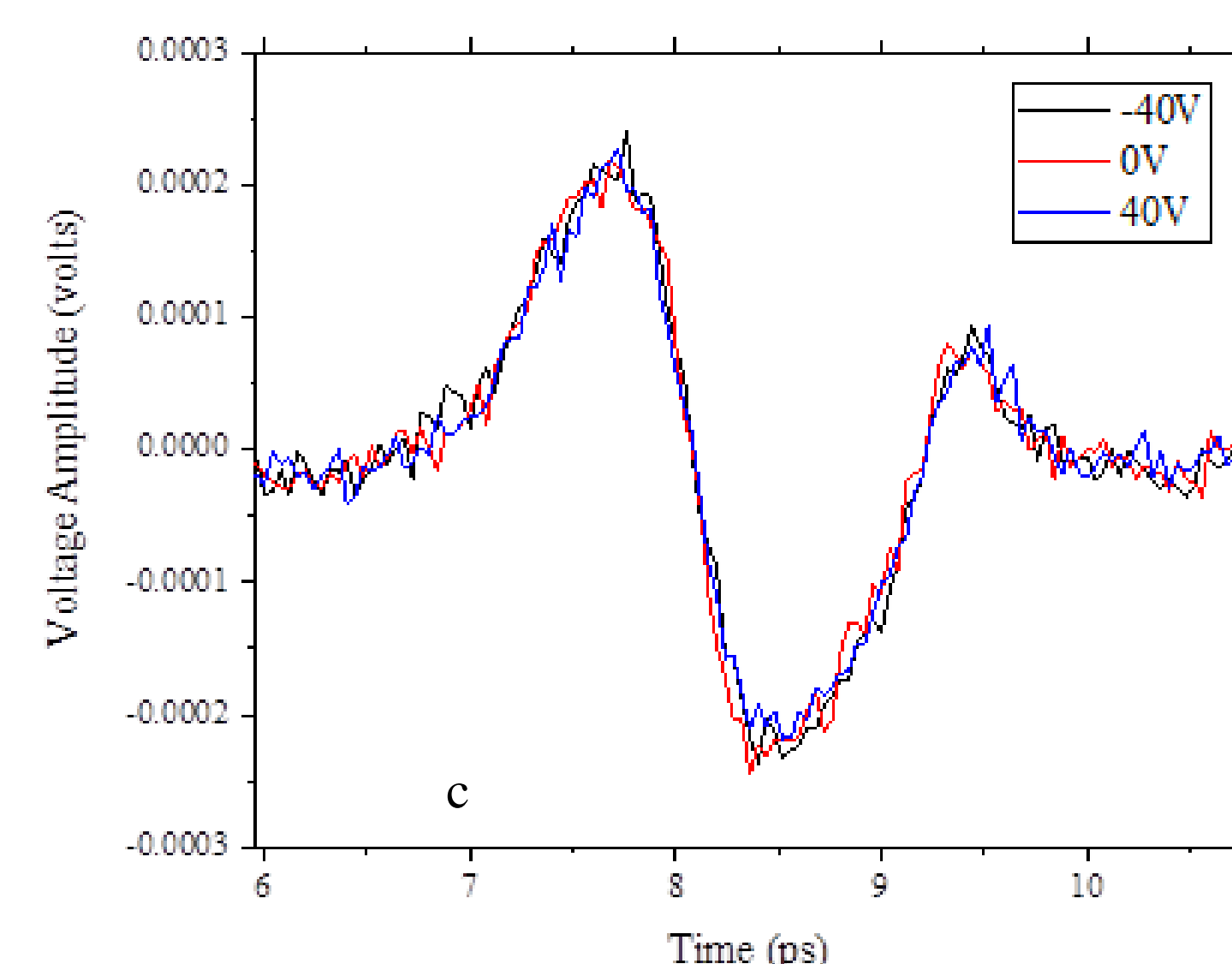


Fig. 6: a: Plots of the THz waveform generated using the sample containing CNT. Different voltage biases were applied to the sample in order to observe the relationship with pulse amplitude and voltage bias.

## Raman Spectroscopy of CNT Sample

- Half-width half maximum of D-band (1350 cm<sup>-1</sup>) is relative to the number of impurities present in the CNT [4].
- Calculating ratio between D-band and G-band (1590 cm<sup>-1</sup>) gives a relative measurement of amount of defects present in the CNT [4].
- Analysis was done for area around dipole and the burning of CNT sample shown in fig 7b and 8c.

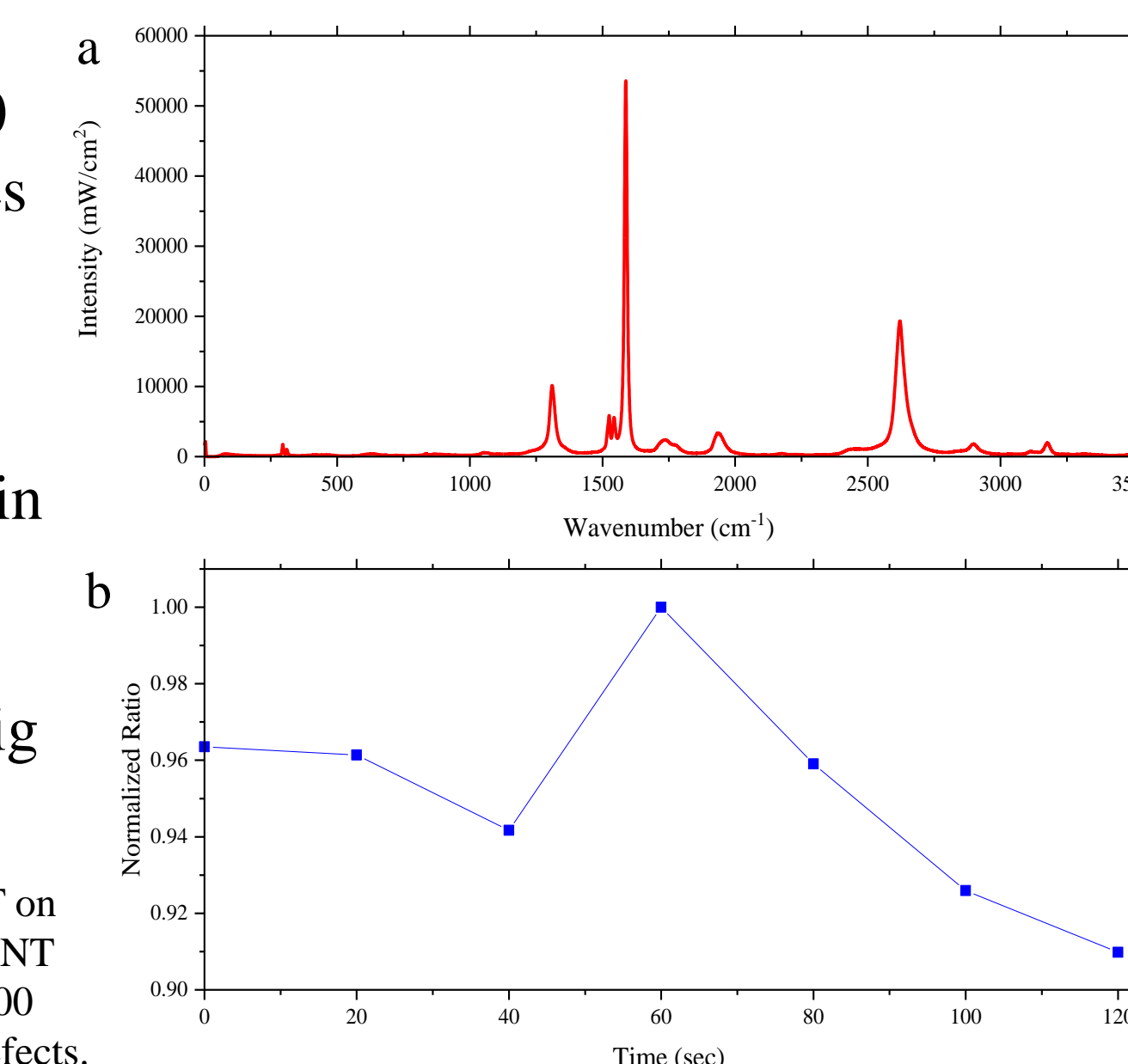
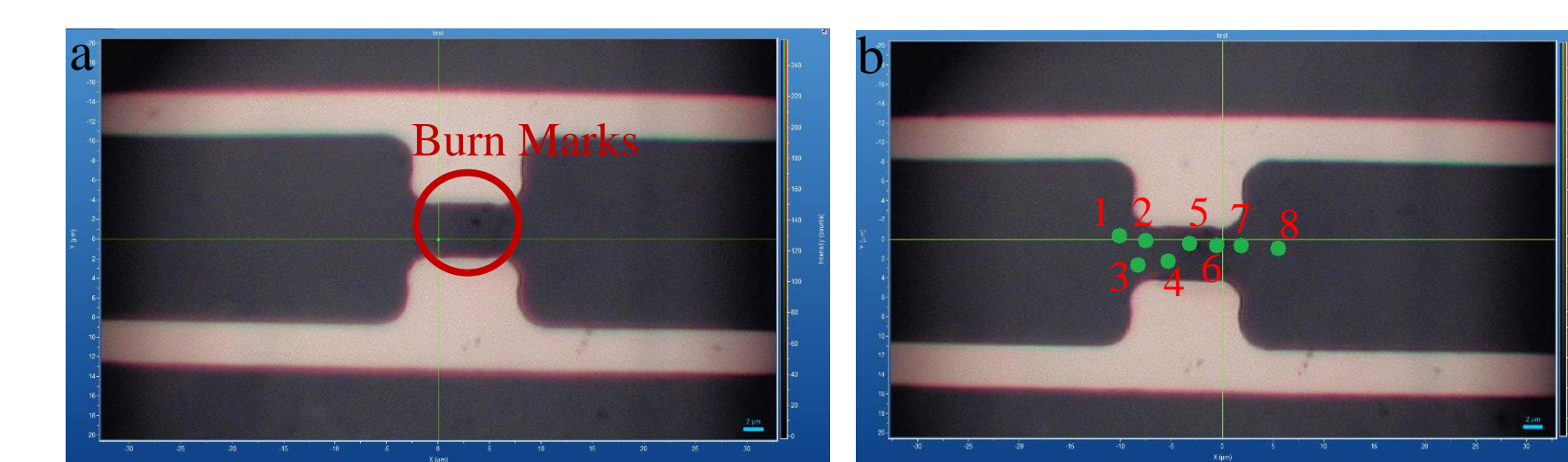


Figure 7: a: Raman Spectrum of CNT on PCA. b: Relative defects present in CNT sample. Data is normalized so that 1.00 corresponds to the least number of defects.



Location	1	2	3	4	5	6	7	8
Ratio	0.695	0.682	0.689	0.461	1.000	0.640	0.492	0.655

Fig. 8: a: Image of the dipole on the CNT sample showing apparent burn marks. b: locations around dipole where Raman spectra were taken. c: Ratio of the HWHM of the D-band and G-band which is relative to the number of defects present in the CNT for the locations in b.

## Summary

- THz radiation can be generated from silicon or gold using UV light. Mechanism is unknown, requiring further research.
- Appears that CNT cannot generate THz radiation when illuminated with a UV beam.
- Resistance of the CNT sample increases in resistance when exposed to UV light.
- When CNT sample was observed under a microscope, there appeared to be a circular burn mark inside the dipole.
- CNT (6,5) Raman Spectra not observed within dipole, suggesting CNT not present.
- Exposure to 532nm focused high powered laser may damage CNT, resulting in smaller Raman Spectra peaks. May explain burn marks on sample CNT dipole.

## Future Work

- Repair of Inspire will allow experimentation with visible light utilized as pump.
- Installing Cryostat will permit low temperature experiments and create a near zero oxygen environment for CNT.
- New CNT samples from Rice University will allow for a higher voltage bias and permit increase in spreading of gold electrodes on CNT.
- Use of high powered setup will permit access to additional wavelengths.

## Acknowledgements

This research was made possible through the generosity of the Nakatani Foundation and the mission of Osaka University – Institute of Laser Engineering -- to connect researchers from around the world to advance science.

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