Thesis Talk Notes

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1 Introduction

1.1 Results

- The goal of this project was to find the complex index of refraction for aligned MWCNTs in high-strength terahertz fields.
- The outcome of the project was promising, but the results show that further refinement to the techniques used is needed.

1.2 Motivations

- All of you will have heard of carbon nanotubes, they're an exciting material with prospective applications in medicine, nano-electronics, and countless other fields. But before we can make full use of carbon-nanotubes, we need to understand their properties.

1.3 Project Goals

- As I stated before, the goal of this project was to model the transmission of high field-strength terahertz radiation through a specific nanotube sample.
- This model was then compared to transmission data taken in Dr. Lee's lab to find the frequency dependent complex index of refraction.

2 Background

2.1 Index of Refraction

- The index of refraction is a material property that describes the way electromagnetic radiation behaves inside of matter.
- The real part of the complex index of refraction is usually just called the index of refraction, and is used to determine things like how light refracts in, or reflects off of matter.
- The imaginary part is often called the extinction coefficient, and it describes the degree to which light is absorbed by the medium it is traveling in.
- This project aims to measure both parts simultaneously for a multi-walled carbon nanotube sheet aligned parallel to the polarization of the incoming pulses.

2.2 Nanotubes

- The nanotubes involved in this experiment were multi-walled, meaning they were comprised of multiple concentric tubes, each of which is formed from a single layer of carbon atoms.
- The samples involved were also highly aligned, meaning the axes of the individual tubes are parallel as opposed to distributed randomly or otherwise.
- This alignment is made possible by wrapping the tubes around a polyethylene reel as shown.
- This geometry means that the terahertz pulses actually pass through two sheets of multi-walled carbon nanotubes, each of which is 125 nm thick, as well as the layer of air between which is 500 micrometers thick.
- The data I compared my model to was collected with the reel positioned such that the axes of the nanotubes were parallel to the polarization of the terahertz pulses.

2.3 Terahertz

- I'm going to talk a bit now about the terahertz pulses this project is focused on.
- The terahertz band lies between the infrared and microwave on the electromagnetic spectrum, with one terahertz corresponding to a wavelength of 0.3 mm.
- The terahertz spectrum, which was traditionally difficult to study due to a lack of effective generation and detection schemes, has become far more accessible in the last twenty years or so, prompting a lot of interest in it's study across many fields.
- Furthermore, carbon nanotubes are known to exhibit a strong non-linear response to terahertz radiation, motivating this investigation on their complex index of refraction in the terahertz regime.

3 Methods

3.1 Terahertz Generation/Measurement

- The terahertz pulses used to take the transmission data I analyzed were created using the method of optical rectification.
- An 800 nm laser pulse reflects off an angled grating, which tilts the reflected wavefronts.
- These tiled wavefronts that emerge then enter a lithium niobate prism, and reemerge with a wavelength on the order of 100's of micrometers, or, put another way, as a pulse with a spectrum centered around 0.8 terahertz.
- These terahertz pulses, which are polarized parallel to the axis of the nanotubes, then pass through the sample and are measured by a silicon bolometer, allowing extraction of both the intensity and the spectral phase.
- Here we see an example of one such measured pulse,

3.2 Analysis

- We model the transmission by considering what happens in each layer of the sample.
- Inside both carbon nanotube layers, as well as in the air between them, the light may reflect back and forth many times before being transmitted out.
- The transmitted beam is thus a superposition of the portion of the wave that reflects internally every possible number of times.
- This is called the Fabry-Perot effect.
- The expression for the transmitted wave is a geometric series, which converges since every term is less than zero and decreasing in magnitude as we consider more and more terms.
- Without too much trouble we can evaluate this geometric series to simplify the expression for the transmitted wave.
- We can use the expression for the transmitted beam as the incident beam for the next layer, and so write an expression that accounts for the Fabry-Perot effect within all three layers of the sample.

3.3 Minimization

- Full analysis using the Fabry-Perot effect and considering the absorption inside of each medium yields this complex transmission function.
- Next I use these functions to quantify how closely the model I constructed matches the experimental data.
- This equation called the error metric includes information about how both the modulus (or the magnitude of the complex transmission) and the argument (that is, the angle it makes in the complex plane) compare to those of the measured data.
- The use of such a metric is important because we don't know ahead of time exactly how the transmission will behave as a function of its complex refractive index. The error metric and its component functions on the other hand take the simple form of planes when plotted against the index of refraction or the extinction coefficient.
- The values of the index of refraction and extinction coefficient that minimize this error metric are the parameters that corresponds to our physical measurements.
- I wrote a program that finds the minimum of the metric for several hundred frequencies between 0.5 and 1.5 terahertz, the approximate spectrum of the terahertz pulses.
- As you can see, for any given frequency the error metric may have more than one local minima. This is accounted for in the algorithm I used by specifying a starting "guess" near the minimum known to represent the physical result. For some frequencies, there is only one local minimum that represents both a positive index of refraction and extinction coefficient. This minimum can be "tracked" as the frequency changes, indicating the correct minimum.
- The program updates this guess to the location of the minimum at each frequency step, and so "follows" the minimum as it moves with frequency.

4 Results

4.1 Present Results

- This graph shows the results of that minimization procedure.
- The problems with these results are immediately apparent.
- Both quantities are lower than expected for this material, and you can see that the graphs start behaving poorly at the upper end of the spectrum, which was also not expected.
- However, the general trends that I expected to see are also apparent. Both the index of refraction and extinction coefficient are shown to decrease with increasing frequency.

4.2 Discussion

- These results indicate that while this method is promising for determining complex index of refraction in the terahertz regime for a sample, the technique requires more refinement.
- It is most likely that either the model used is incomplete, or that the method of minimizing the error metric is not perfect.
- Further work on this project would include perfecting the technique and then applying it to other samples and sample geometries to determine their complex index of refraction.

5 Acknowledgments

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- Questions?