

# Progress Towards A Squeezed Light Enhanced Zero-Area Sagnac Interferometer

Matt Reagor<sup>1</sup>

University of Notre Dame, Notre Dame, IN

Tobias Eberle, Sebastian Steinlecher, Joran Bauchrowitz, Prof. Roman Schnabel

Albert Einstein Institute for Gravitational Physics

Hannover, Germany

Received \_\_\_\_\_; accepted \_\_\_\_\_

Aug. 20<sup>th</sup>, 2009

---

<sup>1</sup>Under funding from the 2009 NSF REU Program through the University of Florida

## ABSTRACT

I report on the current progress towards enhancing a zero-area Sagnac interferometer by the injection of a squeezed coherent state and discuss my role in the project. The Sagnac interferometer has recently gained attention from the gravitational wave community after Yanbei Chen<sup>1</sup> demonstrated that the Sagnac interferometer is sensitive only to the time dependent path length of the interferometer's arms and is therefore automatically a quantum non-demolition device, uncoupling radiation pressure from quantum shot noise. This summer, work began at the Albert Einstein Institute for Gravitational Physics (AEI) to build a table-top Sagnac interferometer in order to demonstrate the compatibility of recent advances in squeezed coherent state implementation and the Sagnac topology.

*Subject headings:* REU, squeezed light, Sagnac topology, gravitational wave detection

## Contents

<b>1</b>	<b>Quantum Shot Noise</b>	<b>3</b>
<b>2</b>	<b>The Squeezed Coherent State</b>	<b>5</b>
<b>3</b>	<b>The Zero-Area Sagnac Topology</b>	<b>8</b>
<b>4</b>	<b>Personal Contribution</b>	<b>9</b>
<b>5</b>	<b>Current Progress &amp; Outlook</b>	<b>16</b>
<b>6</b>	<b>My Time in Germany</b>	<b>17</b>
<b>7</b>	<b>Concluding Remarks</b>	<b>18</b>

### 1. Quantum Shot Noise

Today's gravitational wave detectors are limited by several factors, but in the regime from about 100Hz and higher, these detectors are limited by quantum shot noise. This noise arises from fluctuations of the quantized electric field, as explained by quantum optics. Quantum optics generalizes the Heisenberg Uncertainty Principle to quadrature operators, wherein the uncertainty of a particle's position ( $\Delta x$ ) and its momentum ( $\Delta p$ ) is related to the uncertainty of photon number ( $\Delta\chi_1$ ) and the phase ( $\Delta\chi_2$ ) of the electric field:

$$\Delta x \Delta p \geq \frac{\hbar}{2} \Rightarrow \Delta\chi_1 \Delta\chi_2 \geq \frac{1}{2} \quad (1)$$

The inherent uncertainty of the phase quadrature turns out to be a problem for interferometric gravitational wave detection. This is because the beam splitter used in the common

Michaelson interferometer couples its input ports. The common picture of the Michaelson interferometer is misleading in a way (Fig. 1)

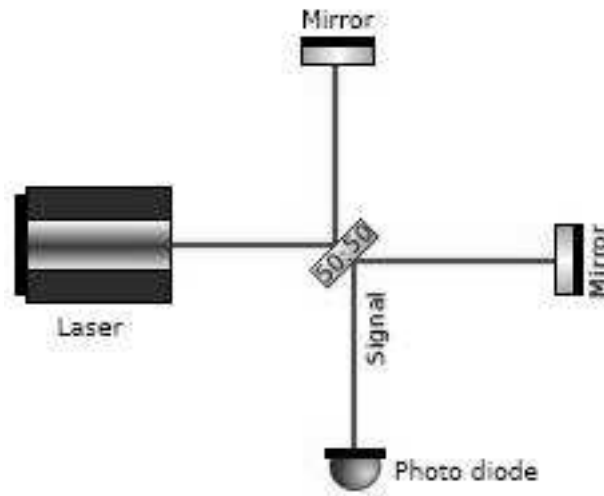


Fig. 1.— A Michaelson Interferometer

The output port of the interferometer, where the photo diode is located, acts as an input port as well, since if we were to shoot a laser beam through the beam splitter from that direction, the two beams would be coupled together (Fig. 2). This is an obstacle for gravitational wave detectors because the intrinsic uncertainty of the phase quadrature of light as mentioned above applies to the vacuum state of the quantized electric field as well. In other words, the vacuum state is comprised of a constant fluctuation of the number of photons present and the phase of those photons. Since beamsplitters couple their input beams as shown above, the vacuum phase noise is coupled into the measurements of the interferometer (Fig. 3).

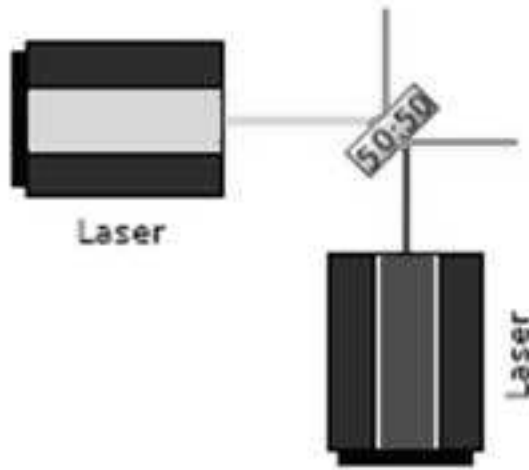


Fig. 2.— A beamsplitter coupling its inputs

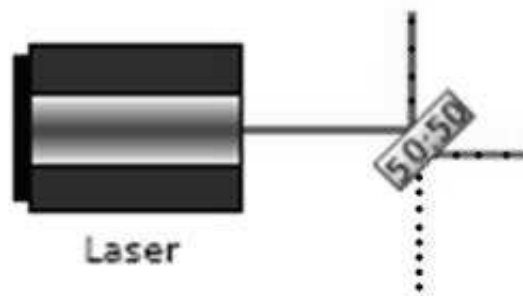


Fig. 3.— The classical Michaelson interferometer coupling in vacuum noise

The gravitational wave community has taken a strong interest in overcoming this quantum shot noise by injecting squeezed light into the dark port.

## 2. The Squeezed Coherent State

A coherent light source, such as a laser, is said to be squeezed if one of the quadratures describing the state is larger than the other. For gravitational wave detection, we are interested in decreasing phase noise. Thus, we inject a squeezed phase quadrature light source into the dark port of the interferometer. The squeezed coherent state is described by

an elegant mathematical representation that relates the destruction of one photon to the creation of an entangled pair, through a process experimentally realized by nonlinear optics as degenerate parametric down conversion. Using a special nonlinear crystal that has been precisely temperature matched, one photon is absorbed and re-emitted by the crystal as two photons of equal frequency - half the original photon's frequency (Fig. 4).

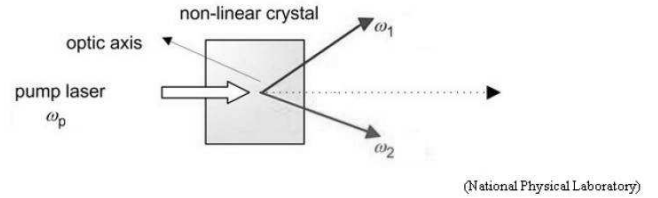


Fig. 4.— Parametric down conversion producing entangled photons

The two photons that are produced through degenerate parametric down conversion will have identical phases, with sidebands of opposite vacuum fluctuations. Thus, if injected into the dark port of the interferometer, the two entangled photons will separate and destructively interfere when recombined. The best way that I have heard this explained was courtesy of Prof. Schnabel at one of our group meetings during the summer. He referred to it as the Dice Picture (Fig. 5).

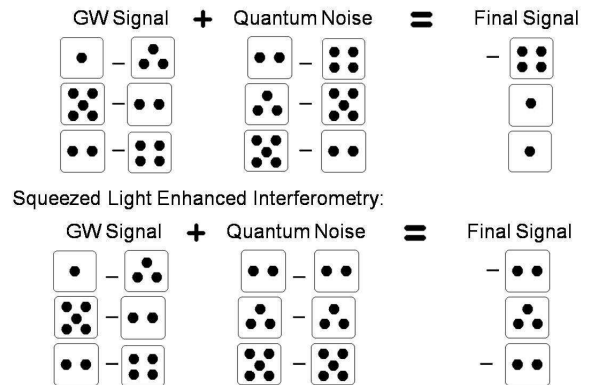


Fig. 5.— Prof. Schnabel's Dice Picture

In this picture, a gravitational wave is represented with a sharp peak; here a measurement of  $(-2,3,-2)$ . The quantum noise is represented by a series of random numbers;  $(-2,-2,3)$ . Without the injection of a squeezed state, the gravitational wave signal is completely masked. However, once the dice are loaded, through degenerate parametric down conversion, the gravitational wave signal is well defined. This is not an artifact of approximation or an unrealistic mathematical construct of quantum optics. Dr. Henning Vahlbruch's thesis provides one of the most stunning examples of the benefit of squeezed state injection (Fig. 6).

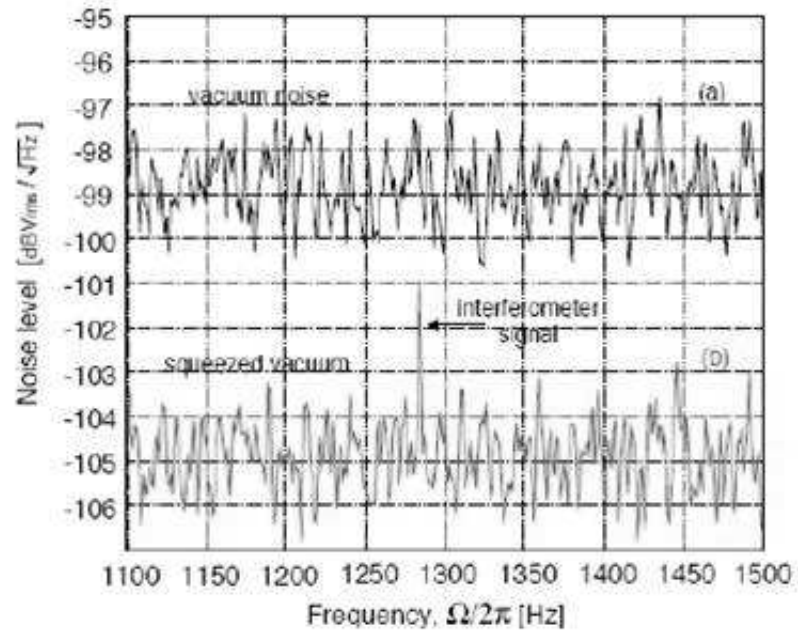


Fig. 6.— A small interferometer signal is undetectable without the benefit of squeezed light.

### 3. The Zero-Area Sagnac Topology

The crucial difference between a Sagnac interferometer and the Michaelson interferometer is that in the Sagnac topology, each photon from the laser impacts every mirror in the interferometer before recombining in the beam splitter. Thus radiation pressure, which is caused by slight power fluctuations in the arm cavities, has little to no impact with the Sagnac topology. Any difference in momentum imparted on the mirrors by power differences will be symmetric and therefore cancel out. A direct comparison between the two interferometer topologies is presented below (Fig. 7).

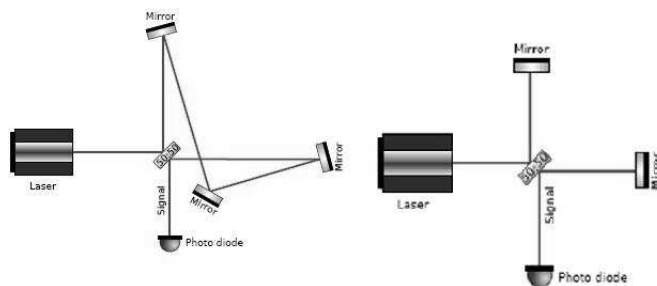


Fig. 7.— The Sagnac and Michaelson topologies.

We refer to the above Sagnac topology as zero-area because even though the laser beams do trace out two triangles with definite areas, these areas are a vector quantity that cancel out since the beams are propagating in opposite directions. If the interferometer has a non-zero area, it will be sensitive to rotations, enough for the rotation of the Earth to become a significant obstacle for gravitational wave detection.



#### 4. Personal Contribution

Before arriving in Hannover, I had worked on optics research at my home institution for almost a year. Thus upon arrival, I expected to know how to do everything that I would be required to do for the summer, or at least have preformed similar tasks in the past. I quickly realized how wrong I was. The original plan was to impliment a Sagnac interferometer on an optics table that had a squeezing cavity already functioning, either Dr. Vahlbruch’s 10dB squeezer at 1064nm, or the squeezer from Tobias Eberle’s diploma thesis at 1550nm. However, the 10dB table had too little room available for our interferometer, and Tobias’s 1550nm laser was under repair, not due back until after summer. We decided to join a group of two students that were just beginning their expirement, which will eventually be an entangled set of squeezers.

The table was bare when we began, which was exciting because it meant that I would get to participate in a world class experiment from scratch. At the same time however, finishing the project by the time I left would be difficult. In fact, several people in Prof. Schnabel’s group, who had worked on similar experiments for much longer were skeptical of our plan, but encouraged the optimism none the less.

My first task on the project was to change out the casings for photodiodes that had been constructed for a beam height of 75mm, since our beam would be at 50mm. I had saudered one or two wires together before the summer, and changing these casings required a delicate touch. So, I devoted some time to practicing saudering first, under the instruction of Andreas Weidner, whose patience and knowledge of electronics helped me gain confidence with a saudering iron quicker than I expected. Changing the casing of the photodiodes was my first real experience with building electronics. I was very impressed by how nearly every electronic component that would be used in our experiment was designed and built at the institute.

After successfully switching the casings, I dove right into the optics side of our experiment, where I was introduced to mode matching. Mode matching is a way of producing a laser beam with precise specifications by matching the resonance of a mode cleaner. The technique begins by careful measurements of the initial beam profile. Knowing these parameters, we fit a series of lenses to the beam, at positions calculated by JAMMT (Just Another Mode Matching Tool). The lenses are followed by two mirrors and the mode cleaner, which is a three mirror cavity designed to be resonant for a specified beam profile. The lenses are calculated and placed to give the desired waist size for the mode cleaner. The pre-mode cleaner mirrors allow the beam to be steered and straightened, so that the beam can be placed precisely in the center of the mode cleaner. The mirrors of the mode cleaner create a standing wave within the cavity, where various resonances are excited. The goal is to only excite the TEM<sub>00</sub> Gaussian mode. A schematic of mode cleaning is presented below (Fig. 7).

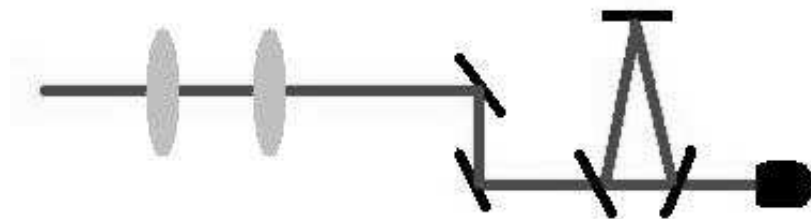


Fig. 8.— Mode cleaning

The length of the mode cleaner is varied across a short distance by a piezo mirror attached to the cavity's back mirror. This ramping allows a photodiode placed after the mode cleaner to detect transmitted light for each excited resonance. We then walk the pre-mode cleaning lenses across the mode cleaner until there are only two peaks present on the oscilloscope, one being the TEM<sub>00</sub> mode and the other being a higher mode (such as the

TEM12 mode) caused by imperfect lens placement. Then, we change the lens configuration slightly and re-maximize the TEM00 mode with the beam walking mirrors.

With the first attempt at mode cleaning, we achieved a mode matching of about 75%. We expected and hoped this to be as high as 90-95%, since imperfections in mode matching equates to losses of power in higher order modes. After several days of trying to improve this mode matching, we decided to wait until the team working on the Second Harmonic Generator (SHG), finished their mode matching, since they were working with nearly an identical beam profile. If they were able to obtain a better mode matching, than the problem was not with the laser, but with our mode matching.

While waiting for the SHG results, I was back to the electronics lab, where I made several small electrical components for our experiment, such as 4-Pole Lemo to 1-Pole Lemo adapters. After awhile, it became fairly clear that the SHG would take a little longer than expected, so we decided to progress with the mode cleaner as is, and fix it later, since as long as the mode cleaner stayed where it was, changing any components before it would leave all alignments/components after the mode cleaner completely unchanged.

For our interferometer, we planned to use an Electro-Optical Modulating (EOM) crystal to simulate a gravitational wave signal. By passing an oscillating electrical signal across the crystal, one can change the optical path length through the crystal. This difference in path length would be compared to the difference in path length in the interferometer caused by the presence of a gravitational wave. In order to use the EOM for this purpose, we needed to know how strongly the crystal modulated this path length.

My first independent optics task of the summer was to set up an apparatus to measure the EOM's behavior. I aligned a Mach Zehnder interferometer directly after the mode cleaner with the EOM crystal in one of the path lengths (Fig. 8 below). One of the mirrors on the interferometer was modulated with a piezo mount, scanned over more than

a wavelength. While this piezo was scanning, I aligned the interferometer to high precision by maximizing the destructive interference caused by this scanning.

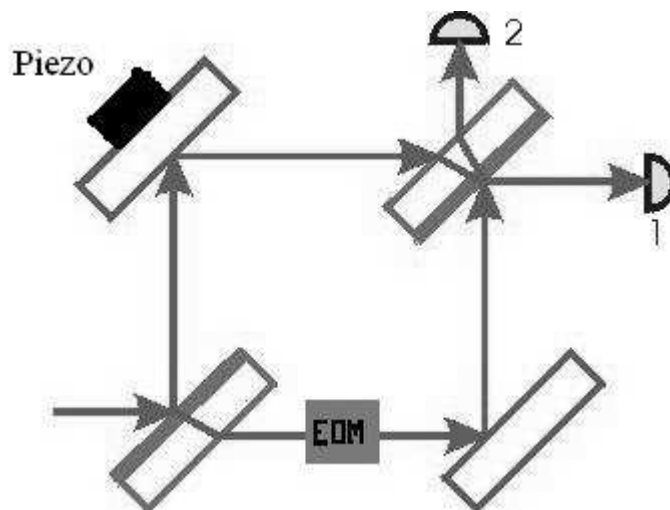


Fig. 9.— Analyzing the EOM with a Mach Zehnder interferometer

After reaching an optimal contrast, I locked one of the photodiodes, the slower of the two, to the midfringe of the piezo-mounted mirror. Since the servo was locked on the midfringe of a sine function, any drifting from the lock position generated an impulse back to the lock position. I then attached the fast photodiode and the EOM to a network analyzer and took the Fourier transform of the interferometer. The network analyzer measured the output of the interferometer as a function of input frequency on the EOM. The idea was to find a resonant frequency of the EOM that modulated the beam to a desired amount, comparable to the signal generated in Dr. Vahlbruch's thesis work above. An example of one of these transfer functions is presented below (Fig. 9).

Around 6.5MHz was the type of EOM resonance we were looking for. I also tested to see if the modulation strength depended on the polarization of light or the input power of the interferometer. I found small effects due to these changes, but not significant enough to adjust our future plans for the Sagnac.

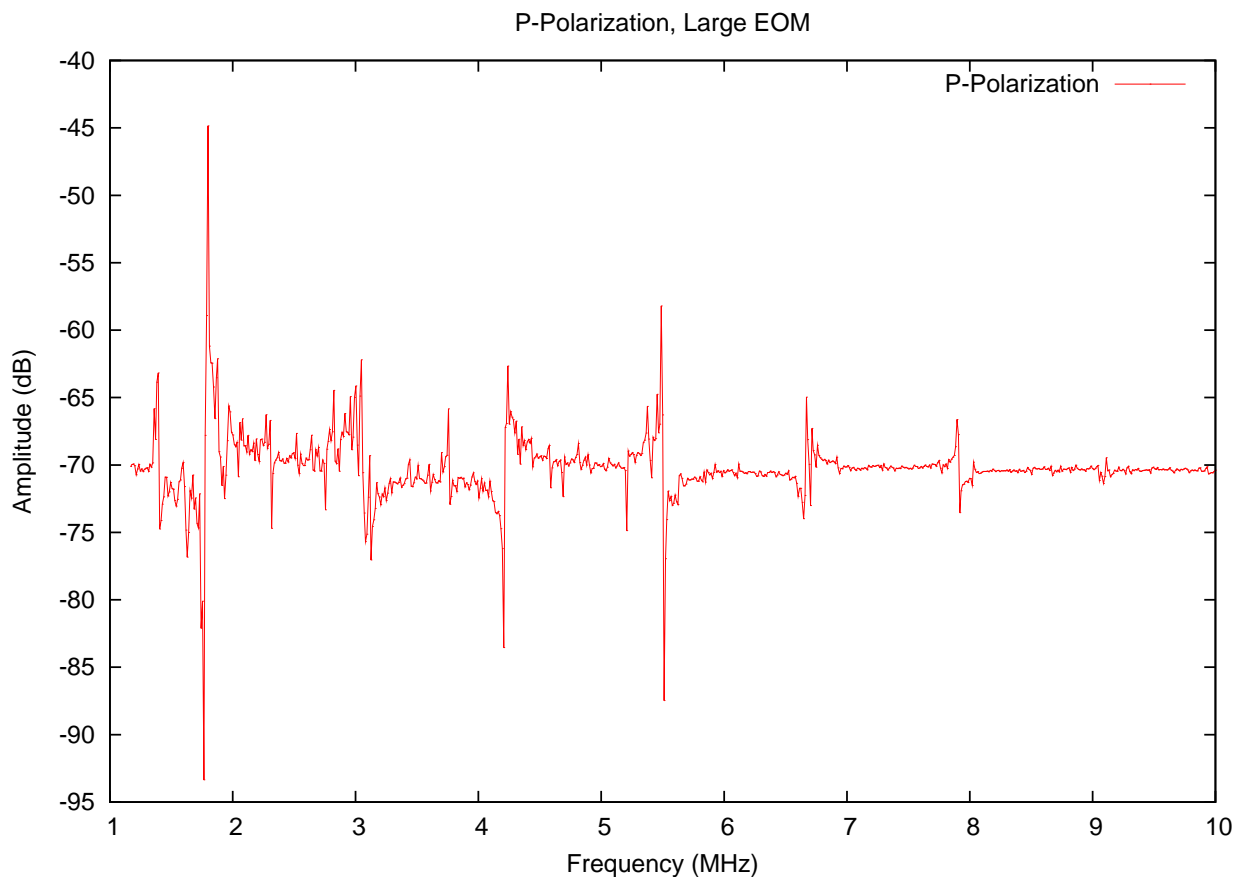


Fig. 10.— Transfer function of an EOM

Since the transfer function looked good, I moved on with the experiment, aligning a mode cleaner after the EOM, which would be used to align the squeezed light into the interferometer. After maximizing the mode cleaning, I found several small modes were being excited. We determined that these were coming from the EOM, due to clipping the sides. I then spent several days re-aligning the EOM and trying various methods of ridding the mode cleaner of these higher modes. Finally, someone in our group suggested we use a larger EOM crystal. We had not been aware of this EOM’s existence at the institute since it was in a back storage closet in another lab. My next task was to check the transfer function of the new EOM and compare it to the old one. I found them to be striking similar

(Fig. 10).

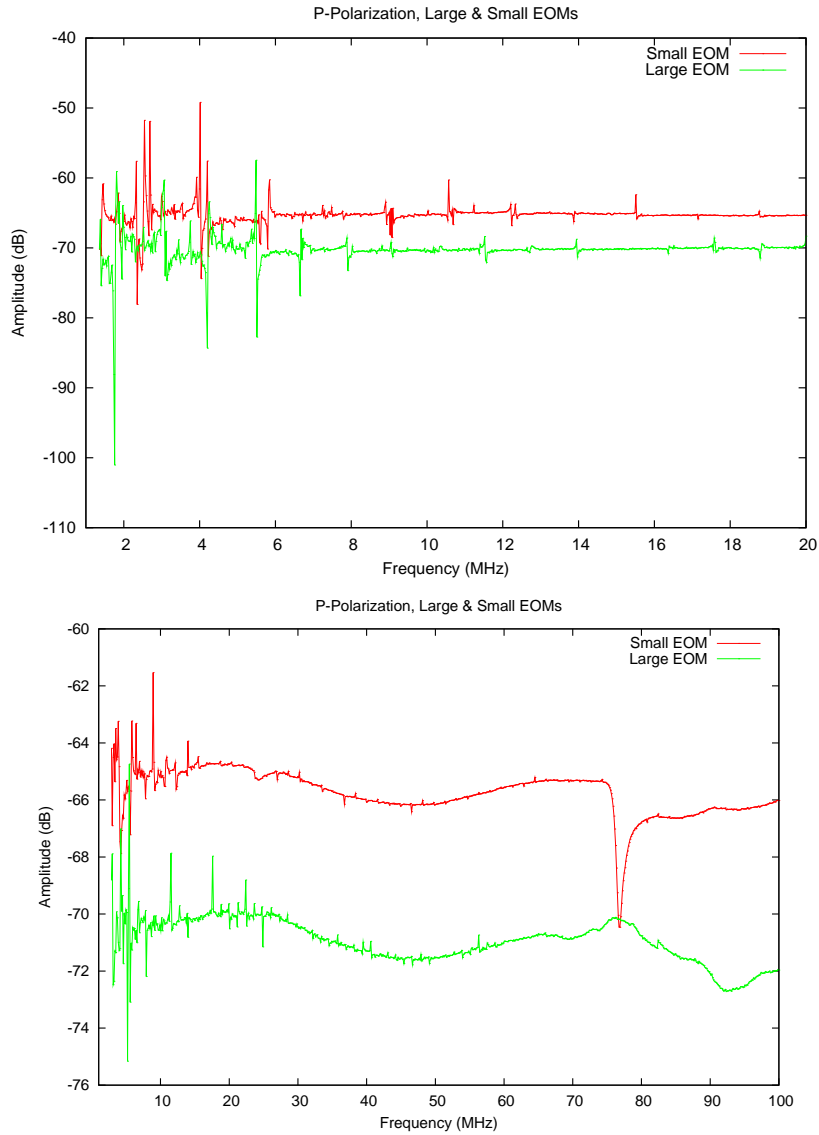


Fig. 11.— Comparing the transfer function of the two EOMs

Since the new EOM produced the same type of resonances that we were able to get out of the smaller crystal, the next task was to test it with the mode cleaner. If the small higher modes were removed, the problem was solved. With the old EOM, I was able to get a mode matching of 97%, but since this mode cleaner would be used to align the

squeezed light source, any imperfection in the mode matching directly corresponded to losses of squeezed light in our interferometer. So, our goal was a mode matching of at least 99.5%. With the new EOM and some very dedicated hours, I was able to adjust the mode matching lenses to obtain 99.94% power in the TEM00 mode. When I reported this at the next group meeting, someone joked that I should do all the mode matching for the group. I politely declined.

Finally, in the second to last week in Hannover, I was able to start aligning the Sagnac interferometer. The Sagnac was particularly hard to align because unlike mode matching, it was impossible to tell where the error in the alignment came from. I measured the contrast (eq. 2 below) of the dark port with a very sensitive photodiode, minimizing the signal as I walked the mirrors.

$$\frac{P_{bright} - P_{dark}}{P_{bright} + P_{dark}} = Contrast \quad (2)$$

To get an lower limit on the contrast, I would scan one of the beams away from the other, corresponding to a minimum interference between the two beams on the photodiode. With this method, I was only able to obtain a 94% contrast, and again the goal was 99.5%. Tobias suggested that I measure the contrast with a power meter instead. This was difficult since the power of the dark port was comparable the background noise of the room. With this method, I measured a lower bound on the contrast to be 98%, which was a little better, but still frustrating that it had not met expectation. After more tweaking, I decided to measure the contrast with more power in the interferometer, increasing it from 10mW to 1400mW. With this increase in power, the dark port's output power became 2mW, instead of 12uW, which was much easier to measure. With this increase of power, I was able to measure a contrast of 99.8%, within the desired specifications.

On my last day in Hannover, I was able to demonstrate how much I had learned from

my time there. In that day, I built a delay loop for the homodyne detector's local oscillator and set up the mode cleaner that will be used to match the interferometer's beam profile to the local oscillator. When I left the lab for the last time, the mode matching for this mode cleaner was at 99.95%. Although the project still has work left, I am confident that my main three contributions, the two mode matchings and the Sagnac's alignment will remain as I left them.

## 5. Current Progress & Outlook

Although we did not finish the experiment by the time I left Hannover, we got far enough that it may be finished soon. The experiment is made of four crucial parts: the SHG, the squeezing cavity, the Sagnac interferometer, and the homodyne detector. Of these four, two were completed upon my departure (the SHG and Sagnac), and the homodyne detector was nearly complete. It became apparent in my last weeks at the institute that we would not have squeezing by the time I left. This made me nervous that the project would never be completed because the group I was working with all had their own projects that were more important. Tobias was beginning work on a very interesting 1550nm quantum information experiment, while the other two would possibly move onto their entanglement experiment.

My goal was then to set up everything Sagnac related, so that when the squeezed light source was finished, it could simply be injected into the Sagnac and measured. Unfortunately, one of the components that would have made this possible, a Faraday isolater, was being used on another table. However, I believe that I was able to progress the Sagnac enough to justify the group spending a few days to finish up the project after the squeezer is operational.



## 6. My Time in Germany

Although I pulled several long shifts in the lab, I did not spend the entire summer there. Interacting with the people in Hannover was very enjoyable and educational. I learned that the hoch-Deutsch are outgoing, kind, and very forgiving of my butchering of their language. From my first weekend in Hannover, the PhD student/larger research community went out of their way to include us (myself the others in the program), in nearly everything they did for fun, be it something simple like the frequent trips to the beer gardens, or more involved like including us in a trip to Hamburg. I cannot say enough about how great the people at AEI were, so I'll leave it there.

The living situation in Hannover was great as well. Frau Franke, who ran the guest house in which we stayed was very involved in getting us accustomed to life in Hannover from the beginning. Our second night in Hannover, she took us to a local choir's performance at the school her kids had attended. Frau Franke also let us borrow bikes for the summer, which granted us a huge freedom to explore more of Hannover, which was a beautiful city.

As a physics major, one generally has to choose between studying abroad and delving deeper into physics. At Notre Dame, the spring semester junior year is the traditional semester to go abroad, but doing so would have meant passing up on my only opportunity to take Quantum Optics and would mean postponing the second half of quantum mechanics and E&M until the following spring, after I am required to take the GRE. This program allowed me to get the benefit of study abroad without having to compromise my physics education.

## 7. Concluding Remarks

I would like to take this time to thank the organizers of the program in which I participated this summer, the University of Florida's International REU for Gravitational-Wave Physics, as well as everyone at AEI that made my time there so extraordinary.

## REFERENCES

Chen, Yanbei, Phys. Rev. D., 67, 12, 2003

Vahlbruch, Henning, "Squeezed Light for Gravitational Wave Astronomy," PhD Thesis, 2008

Moritz, M., et al., "Observation of cw squeezed light at 1550nm," Optics Letters, 34, 7,  
2009

Black, Erik, "An Introduction to Pound-Drever-Hall Laser Frequency Stabilization," AAPT,  
2000