Birefringence Measurement Instrument & Software

ECE 480- Senior Design

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Executive Summary

The Fraunhofer Research Center challenged the design team with developing a diamond optics measurement system that measures stress and impurities within synthetically-grown diamond samples. To accomplish this task, various engineering methods were used. The design team worked to construct a cost-efficient, high quality prototype that displayed the birefringence measurements within diamond sample. The team succeeded in designing a device that displays the intensity of impurities in a synthetic diamond. The success of this device will allow Fraunhofer to quickly analyze the impurities within their synthetically-grown diamond samples as well as save the birefringence measurements. In addition, Fraunhofer will be able to quickly compare and analyze diamond samples without having the physical diamonds present.

Acknowledgement

The members of Design Team 12 would like to not only acknowledge Fraunhofer LLC, but Shannon Demlow, our generous sponsor, as well; the Design Team 12 facilitator, Dr. Virginia Ayres, helped the team overcome difficult obstacles as well as provide great insight into birefringence; Professor Timothy Grotjohn and Professor Lalita Udpa, the course instructors; and the College of Engineering at Michigan State University.

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1.1 Objective

The objective of this project is to improve an existing birefringence measurement system for diamond optical properties that was created by a senior capstone team in 2013 for Fraunhofer. Because of Fraunhofer’s dissatisfaction of the measurement performance, the project team is tasked to refine the measurement system from light source, to high resolution
camera for data capturing to better computer interface, and more importantly to achieve higher measurement quality. With an improved measurement system, Fraunhofer will be able to better examine and quantify the quality of their synthetic diamonds. This will also allow Fraunhofer to exchange diamond data without requiring physical presence of the diamond.

1.2 Scientific Background

It is important to understand the science of light and birefringence in order to understand how the solution of this design. Light can be characterized as having only vertical and horizontal components and when it interacts with a medium can be reflected and or refracted. This refracted light is light that gets transmitted through the medium in which the incident light approaches. The angle at which the refracted light travels through the medium is partially dependant on what is known as an index of refraction. Every medium has an index of refraction and refracted light that travels through the medium is known as an ordinary ray. However, when the medium or material the light travels through has multiple indicies of refraction that material is said to be birefringent. Light passing through a birefringent material will have more than one index of refraction and thus it will have more than one angle of refracted light. The refracted light from the other unexpected indices of refractions are known as extraordinary rays. This means that if there is a method for determining whether or not extraordinary rays exist then there is a way to determine whether or not a material is birefringent. Stressed diamonds are birefringent so detecting extraordinary rays going through a diamond will tell us if there are stresses in the diamond.

To determine whether or not a material is birefringent or not we have to use a cross polarizer. Polarizers pass light of certain orientations while blocking others. A vertical polarizer passess the vertical component of light while a horizontal polarizer only passess the horizontal component of light. Since light can be characterized as only have vertical and horizontal components, using a vertical and a horizontal polarizer can block out light entirely. If light passes through a vertical polarizer then only the vertical component is left because the vertical polarizer would block out the horizontal component. Then, when the vertical component passes through a horizontal polarizer none of it would go through because there is no horizontal component in vertical components of light. This means that if light were to approach a vertical polarizer followed by a horizontal polarizer, there would be no light coming out of the opposite end.

When light enters a material or medium perpendicularly, the ordinary ray is also going to
be perpendicular. Therefore if a non birefringent material is placed in between a vertical and horizontal polarizer, no light passes through the polarizers because the ordinary ray still only has one component which gets blocked out. However, if a birefringent material or stressed diamond is placed in between a vertical and horizontal polarizer, the stressed diamond or birefringent material will create an extra ordinary ray which is not perpendicular. This means that the extra ordinary ray will have vertical and horizontal components even if the light has already passed through one polarizer before it approaches the stressed diamond. Since a polarizer can only block out light of one type orientation, part of the extraordinary ray will pass through. So if a stressed diamond is placed in between a vertical and horizontal polarizer and light gets shot through polarizers and diamond, there will be visible light that goes through all three of these materials.

Chapter 2: Exploring the Solution Space

2.1 Customer Requirements

Our customer, Fraunhofer Center for Coatings and Laser Applications, needs to a system that is capable of measuring and locating the impurities of an artificially grown diamond. These impurities can be detected as a result of the optical quality known as birefringence. A birefringence measurement is calculated based on the difference between the light intensity that shines through the diamond. This birefringence calculation creates quantifiable data of diamond stress and allows Fraunhofer to exchange diamond data without needing to have physical diamonds present.

The first parameter that must be met is to create a system that disallows the transmission of ambient light into the system. If ambient light is capable of entering the system, it will alter the light intensity of the diamond image and, thus, skew the birefringence calculation. To account for this error, the outer shell containing the diamond sample must be thick enough to block out all exterior light. If the shell is too thin, the structure will not be strong enough to protect the contents and will not be able to shield ambient light.

Another requirement that must be fulfilled to meet the customer expectations is to have a light source that is capable of illuminating the entire diamond sample. When the source is
illuminating light, it must do so in such a way that the light is being distributed uniformly. This is important, because this will allow all image pixels to receive the same amount of light and, thus, create an accurate representation of light intensity.

The customer also expects to have the resolution of the camera accurately depict the diamond image. This is a critical parameter, because in order to calculate the exact value of birefringence, the diamond quality must be represented as accurately as possible. In order to accomplish this, a high-resolution camera source must be used. This camera must be located in a position to capture ever pixel of the diamond as well as be in focus for the user. There are not any limitations on the size of the design, but it makes more sense to have a design that is compact and portable. The camera must also have USB capability so that the image can accurately be transferred to the software program to calculate light intensity.

Finally, in order to meet the customer expectations, the software must be user-friendly. The software to be used must, therefore, specifically be made for creating graphical user interfaces. In addition, the software must calculate the birefringence correctly. This means that the software to be used must focus on image processing. This is a very important parameter, because the software is the driving force behind the implementation of the design and is responsible for accurately calculating birefringence.

2.2 Design Specifications

Often times, diamonds have stresses within them, which can be detected through an optical quality known as birefringence. The sponsor requires an optical measurement device to detect the level of birefringence that occurs in artificially grown diamonds. There are several specifications that are required to be implemented in this design. The team will follow the step-by-step approach, so the demonstration of the design specification will occur in a particular order.

First, to detect birefringence, the design should be immune to exterior light sources. A stable light source and a shell that is impervious to ambient light are required. The previous team used a laser pointer as their light source. However, the laser had a non-uniform distribution of its light, which created spots on the diamond. The current team chose Light Emitting Diodes (LED) as new light source. Compared to the laser, LED’s can generate the same amount of power, but with more uniform and crisp light beams. To obtain and calculate multiple measurements, the team chose six different colors of LEDs, each emitting light at different wavelengths (white, blue,
lime, green, orange and red). For an effective and efficient light source system, the team will test and analyze the different spectrums and characteristics for each LED, resulting in a convincing final lab report. Furthermore, to integrate these LEDs into one light source system, a voltage regulator is required that provides different voltages for each LED. Eventually, a knob switch might be needed to turn on a single output LED.

In addition, the design needs a high-resolution measurement of birefringence. In this case, a high-resolution camera that can effectively detect LEDs is required. The sponsor requests a highly reliable grid resolution of ten micrometers, with a maximum possible error of 1%. Indeed, any higher resolutions are usable as imperfections in diamonds are typically in the parts per million. Additionally, an advanced camera can avoid mechanical movement of the crystal sample because an image movement can be conducted by software. This specification is a significant element for the design and can be completed by a good combination of LEDs and camera.

Finally, the system should interface with a computer and display the data on the computer in the form of a 2-D image, including birefringence associated with a position vector. This image and data are vital to the study of the faults in artificially grown diamonds; locating common patterns will allow the sponsor to determine better possible implementations to achieve a better process. In order for a design to be considered pliable, these sets of data must be present. This specification can be implemented by codes in the advanced software, Visual Studio.

2.3 Initial Solutions

The first build of the system did not feature removable LED light sources and voltage regulator. At this time it was believed that the LED light source just be placed inside the outer shell however the wires that connect the LED light source to the power source were very long and not stable. It also featured a white LED light source. The white LED has much power comparing with other single color LEDs. To operate it, the team ordered a 36 volts/ 1.12 A power supplier. However, the LED would become very hot when the supplier directly power the white LED, and would melt the soldering metal at it was attached to. One of the team design solutions to this was to solder up to twenty five 1.2k resistors or equal impedance value to the white LED in parallel to reduce the current through the white LED and thus decrease the heat of it. However, even with twenty five resistors soldered on in parallel could significantly extend the
using time of white LED but did not stop the white LED from burning the connecting metal. A more complex cooling system should be conducted during the white LED operation, whereas, considering the extremely limited space for light source in the outer shell, the team decided to abandon the white LED. The following figures show pictures of the white LED source and the outer shell of the first prototype.

Figure 2.3-1 Operating White LED
Figure 2.3-2 Optimized White LED
The second build of the solution added a slides to hold the diamond, LED light source,
voltage regulator and located the diamond further away from the lens of the camera. However, this is a problem because it turns out that after testing that the diamond needs to be closer the lens of the camera. Another problem with this design is that the camera is too large so the camera has to be removed in order to slide the door out. The lens was also too large for the outer shell to fit. The following figures show the diamond slide holder and the outer shell with the inner circuitry inside.

Figure 2.3-4 First Build of Diamond Holder
Figure 2.3-5 Second Build of Outer Shell with Inner Components
Chapter 3: Technical Work Performed

3.1 LED Light Source

The LED light source is important because it functions as a light source which the camera is able to detect and determine whether or not the diamond is birefringent. It is desirable to be able to test multiple LED light sources so that different wavelengths can be tested. In order to design for this, the LED light source is placed on a chip in which all the pieces were soldered onto. This way the LED light sources are interchangeable by sliding the LED chips in and out. The wires of the LED are very long for the further adjustments so they had to be taped down. And each LED chip has a removable-plug to connect with power supplier.

Figure 3.1-1 Original Prototype of Light Source with Orange LED on
Be specific, red and orange LEDs are in one chip because they share the same voltage of 2.1 volts, the particular voltage was controlled by two resistors in series which are 10 ohms and 18 ohms. In this way, the team can put both red and orange LEDs be parallel with the 18 ohms which can provide around 2.1 volts for both LEDs. A switch was also added in the circuit to alter the LED. The red LED has a wavelength around 630 nm and orange LED has a wavelength around 616 nm.
Figure 3.1-3 Performances and spectrums of Red LED
The green and blue LEDs share the same method with the previous two LEDs but changed the 18 ohms to 82 ohms because the green and blue need a larger voltage which is around 2.9 volts. A sliding switch was added into these chips to switch one LED to another. The blue LED has a wavelength around 470 nm and green LED has a wavelength around 505 nm.
Figure 3.1-5 Performances and spectrums of Blue LED
Eventually, the lime LED requires a unique voltage so it was set in a single chip with changing the "supply resistor" to 56 ohms to obtain the 2.7 volts operating voltage. In addition, the wavelength of the lime LED is around 517 nm.
3.2 Voltage Regulator

The voltage regulator is important because it powers the LED. All of the LED lights need around 3 volts and the voltage regulator system contains a 100 volts AC to 9 volts DC converter, a 9 volts DC to 5 volts DC voltage regulator and a 5 volts DC to 3.3 volts DC voltage regulator. So it has the ability to convert the voltage supplied by an electrical outlet to 3.281 volts. The components of the voltage regulator are soldered onto a chip which was then manually cut to be able to fit into the outer shell. The following figures shows the design of the circuit and a picture of the finished product from the front and back side.
Figure 3.2.1 Schematic circuit for 3.3 volts voltage regulator [3]

3.3 Outer Shell

The outer shell is important because it holds the inner circuitry in place and shields the design from outside ambient light. The outer shell was designed using a program called NX then the NX file is saved as an STL file so that it could be three dimensionally printed with maker bots located at DECS.

The most important function of the outer shell is to hold the inner design and circuitry. The outer shell must be able to hold the voltage regulator, LED light sources, collimator, the diamond sample, camera system, and the linear and horizontal polarizers. To do that the there
are rungs designed on the walls of the outer shell so that the outer shell can hold these objects in place. The figure below shows the design of the outer shell on the NX file.

![Figure 3.3-1 NX Design of Final Outer Shell](image_url)

The very bottom rungs are meant to hold the voltage regulator in place. The voltage regulator has a wallwart jack attached to it and so the outer shell was designed with that in mind. The hole above the right rung is where the voltage regulator can plug into the wall for power.

Above the voltage regulator is where the LED light source is placed. The LED light source is placed. It has to be directly above the voltage regulator because the wires on the LED light source are short.

The next rungs are for the collimator. A picture of the collimator can be found in the following figure. This is important because the collimator concentrates the light towards the diamond sample and so that more of the light can travel at the direct angle towards the diamond sample.
The next few rungs are designed for the polarizers and diamond sample. The light must pass through a polarizer before it passes through the diamond sample so the rungs designed for the polarizers were designed for a relatively perfect fit. The slot for the diamond sample is placed in the middle and was designed for a little more space because the diamond sample holder has a raised area. The middle of the diamond holder is hollow in the NX design so that a microscope slide can be placed under it to hold the diamond. The NX design of the microscope holder can be found on the following figure.

Other important things to consider when designing the outer shell is that it has to block the ambient light. To do this the entire inner design must be enclosed by the case so that ambient light does not get into the inner design. To do that there is a slidable door created. This way the user and replace and the diamond sample and LED lights while and be able to shield the design from ambient light. The door is designed sideways because the camera system is large and if it were the slide up and down the camera system would have to be removed every time.
the diamond sample is placed in it.

Another consideration is in regards to whether or not ambient light can get into the system through traveling through the outer shell. We are not sure of the penetration depth of light into the type of plastic and printing that is done, so we decided to be safe about the design even though it might be more expensive. The walls of the outer shell were designed to be relatively thick so that light cannot penetrate the outer shell. Then the color of the outer shell was designed to be black so this way it is even harder for ambient light to pass through the shell.

The outer shell also had to be designed such that the dimensions are exactly the size of the polarizers. This is important because light cannot travel in between the polarizers otherwise it would substantially throw off measurements. Therefore the outer shell is designed so that if the polarizers are a perfect fit then less non-polarized light would be detected by the camera. However, it is impossible to stop all non-polarized light from getting into the camera, but the way this is designed allows for a minimum amount to be detected.

It is also important to note that there will be inaccuracies with the three-dimensional printing done at DECS because the maker bots used to do the printing are not very accurate. Therefore once the design is printed there is lots of sanding that must be done in order to make everything fit.

The diamond must also be located as close as possible to the lens of the camera otherwise the camera will get very low quality images so the location of the diamond and upper polarizer is placed directly under where the lens would be of the camera. Due to the fact that the makerbot prints inaccurately sometimes, there was extra room in the diamond rungs so that additional materials could be placed under the diamond to physically move the diamond closer to the lens.

3.4 User Interface and Software Design

The user interface plays a key role in providing a user-friendly process where the user is able to obtain diamond images and create an output image that displays birefringence measurements. Visual Studio was selected as the software of choice to construct this user interface for many reasons. Visual Studio can be programmed in various programming languages, which allows for flexibility between programmers. For the purpose of this project, C++ was the language chosen, because this language is one of the most universal amongst programmers. In addition, this program is specifically designed to revolve around user interface and events. A program with these design specifications allow for a quick and easy experience for
the users. The user interface, designed in Visual Studio, for the Diamond Optics Measurement System is displayed in the figure below.

Figure 5. User Interface

As far as functionality goes, Visual Studio includes many different libraries and classes that assist in image processing. The user interface allows the user to load the initial image without the diamond by selecting the “Calculate Birefringence” menu option and then choosing “Load Image Without Diamond” from the drop-down menu. The diamond is then loaded into the diamond tray of the measurement system and the next image is loaded via the “Load Image With Diamond” drop-down menu. After both images are loaded, the “Enter Diamond Thickness” menu option is selected to enter the diamond thickness. Next, the software traverses each pixel, divides the light intensity of the second image by the first image, and then continues to run the new pixel value through the birefringence algorithm specified in Equation A below.

$$\delta = (2\pi/\lambda) \times (\Delta \eta)d$$

Equation A. Birefringence Algorithm

In the equation above, “\(\lambda\)” represents the wavelength of the light source, “\(\Delta \eta\)” represents the birefringence value, and “\(d\)” represents the specified thickness of the diamond. In order to relate
the equation above to the light intensity of the image pixels, a second equation, specified below, was used.

\[ \frac{I}{I_0} \approx \frac{1}{2} \sin^2(\delta/2) \]

Equation B. Algorithm that relates pixel intensity to birefringence

In the equation above, “I” represents the pixel intensity of the second image and “I0” represents the pixel intensity of the first image. Performing the above equations on the desired diamond image produces and displays a diamond image with its associated birefringence values.

In order to perform the above equation calculations on the diamond images, the “Birefringence” drop-down menu option must be selected. The menu option will then calculate the birefringence values, display a new image with these birefringence measurements, and create a measurement scale that shows a range of different colors that are associated with different values.

Figure 6. User Interface with window displaying both diamond images
Chapter 4: Test Data of Prototype

To obtain the multiple results, the team used different light source to generate the birefringence images. Because the red LED and Orange LED is almost the same because of the similar light spectrum and light power output, the results were similar. The green and blue LED has a lower wavelength which can create more power output, but if the parameter in software was set by preference of Red LED, the green and blue LED’s results could be blurry. So different light sources had different performances on the measurements of the birefringence. These data can be illustrated as following images that the birefringence occurred at spots where has higher intensity.

![Figure 4.1 Test data image for Red LED](image-url)
Figure 4.2 Test data image for Orange LED

Figure 4.3 Test data image for Blue LED
Figure 4.4 Test data image for Green LED

Figure 4.5 Test data image for Green LED
Chapter 5: Summary

5.1 Final Costs

First, there are two orders for the light source system. One is the order of six LEDs (white, red, orange, blue, green and lime). However, the team found that the lime LED is not in the unity with other single color LEDs and the white LED operation required a voltage supplier. Additionally, the LED cannot afford too much head when soldering, the red LED was broken at during soldering process, the team need another red LED. So the second order for light source includes a white LED power supplier, a red LED which same with the previous one and a lime LED share the same characteristics with other single color LEDs. Thus, the first order of light source is $50.77 and the second order is $54.01. Eventually, the final cost of the light source system is $104.78 which showed in the following charts as bellow.

![Figure 5.1-1 Order 1 for light source system](image-url)
There are also costs for the outer shell, collimator and diamond holder. The outer shell with the door costs a total of 13 dollars whereas the collimator and diamond holder each cost a dollar to print. This method of printing was chosen because it is the most cost effective given that prototypes and multiple versions of this design had to be printed.

The costs of the microscope slides for each slide is negligible. However, knowing that there are would lots of testing that needed to be complete the team ordered 40 dollars worth of slides in case some unforeseen event happens with the slides.

5.2 Summary

The final design of the project should cost around 275 dollars total. However, due to testing process the team spent around 400 dollars to complete this project. When looking at different companies that sell birefringence measurement systems online, none of the companies
would provide a cost for this product. However, the team believes that a birefringence measurement system would be sold for thousands of dollars.

Appendix

Technical roles, responsibilities, and work accomplished

Dan Schulz

Dan Schulz was the team manager, and responsible for overseeing and providing input on all aspects of the project. He initially developed the GANTT chart to keep the team on task, and scheduled meetings with Fraunhofer and the facilitator, Dr. Ayres to make sure the team was on task. He also was responsible for scheduling the group multi-weekly meetings, and making sure everyone was contributing to the project.

Schulz was also responsible for ordering the polarized slides, and understanding the physics of birefringence and how it relates to the diamond. He came up with the idea of having multiple circuit boards for each individual LED, which allowed the system to change the light wavelength (color). Along with the rest of the team, Schulz also took images with the camera and made to compare the prototype results to the expected results that Fraunhofer provided.

Dan Schulz also played a significant role in the poster development, and with the help of others, decided which information was most important to be visually displayed on design day.

Allen Lin

Allen Lin was responsible for the presentation preparations and the design of the hardware. The initial template of the technical and introductory lectures was organized by Allen Lin and the team helped out with making edits to those presentations.

Allen Lin designed the outer shell. He used the NX program to design the outer shell, door. These things all had be done very precisely in terms of measurements because the slightest inaccuracy could mean that ambient light detected by the camera. Due to the fact that the maker bots do not print very accurately, Allen Lin had to sand the outer shell and resized all the parts of the inner design to fit the outer shell after all the parts are printed. Due to the many different designs, there were three different outer shells that were printed, sanded and designed.
Allen Lin also designed the diamond holder and the collimator using NX. These parts were also sanded by Allen Lin in order to fit into the outer shell and tested by Allen Lin to make sure that they functioned correctly. The diamond holder also had to have a removeable lens which was also built and designed by Allen Lin.

Allen Lin along with Chunyu Li also designed and built the voltage regulator and LED light source. Even though the final design did not include the use of the white LED light source, Allen Lin and Chunyu Li did extensive testing together to come up with the conclusion that the white LED light could not be used. The voltage regulator was designed using parts that were provided by the ECE workshop at MSU and Allen helped to put these parts together and solder them together on a board. After some testing with the voltage regulator it was initially discovered that it did not work properly and so Allen Lin along with Chunyu Li troubleshooted the voltage regulator and make the necessary changes in order to make sure that the voltage regulator worked properly.

Allen Lin along with Adam Tayloe, Chunyu Li, and Dan Schulz also helped to test the camera and take images to determine how to take a picture such that the entire diamond would fit onto the screen and have it be high quality at the same time.

**Chunyu Li**

Chunyu Li is the team’s lab coordinator and was responsible for the light source design. He participated in the labs of building voltage regulator, light source system and measurements about both LEDs and total system. Additionally, Mr. Li helped to create or revise the light source part in reports or presentations.

Chunyu also re-designed and optimized the light source system because the results of previous team’s designs (both green and red lasers) generated too intensive light which made the image results spotty. To accomplish the new project requirements, he chose a different type of light source, which is the high power light emitting diodes. Thus, Mr. Li tested these light source designs, researched in the lab, after obtained the data, spectrums and light image results of each LED, he selected the replaceable single color LED as the final light source design.

Additionally, to operate the LEDs, he also designed and built the voltage regulator with Allen Lin. As well as giving suggestions towards the design of outer shell and other designs.
Adam Tayloe

Adam Tayloe was responsible for document preparation as well as user interface implementation and software design. Adam researched many different software programs and chose Visual Studio to implement the user interface and birefringence calculation. The user interface contains many self-explanatory menu options that allow the user to load the desired diamond images, calculate birefringence, and then save the output image to a specified location.

Adam designed the software so that once the two images are loaded into the program, Visual Studio compares the light intensities from the images, pixel by pixel, and then runs each pixel through a birefringence algorithm. The output image is then displayed onto the screen, along with a birefringence value scale.

Adam, as document preparation, was responsible for organizing and preparing all documents throughout the course. In addition, Adam helped to assign roles for each document to team members. These documents include progress reports, proposals, application notes, design issues, and reports.

Dan Kuang

Dan Kuang was responsible as the webmaster for the team for publishing the team's website which shows objectives and technical details of the project. He was responsible for the initial design of the diamond placement mechanism to hold the diamond sample in place between the two polarizers by looking for the appropriate part that allows light to pass through while holding the diamond sample. He has also helped researched various microscopes and cameras that could be used for the birefringence measurement instrument to capture the image of the diamond sample. He was also involved in helping in the testing of the camera to ensure it has optimal settings capture a good raw image of the diamond sample before it is sent to software application to measure birefringence.
Literature and website references

