



Experimental Investigation of Twisted Light

A Major Qualifying Project

Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

By

Caleb A. Ruvich

Date: April 25, 2013

Advisor:

Prof. Richard S. Quimby

Departments of Physics

Abstract

Optical vortices and specifically light with orbital angular momentum are a novel type of optical mode. The ability to manipulate and successfully propagate optical vortices in optical fibers would allow for light sensitive optical tweezers, orbital angular momentum state multiplexing for optical communications, as well as possible other uses. The creation and characterization of optical vortices was done using holographic interference. An analysis of the propagation of optical vortices in free space as well as how a mode would act in a fiber showed that a typical single-mode fiber is not able to preserve an optical vortex state. Further analysis of optical fibers will allow for the vortex states to successfully propagate for significant distances. Improvements to the creation process of the holograms will increase the quality of the vortices which will be important for any eventual application.

Acknowledgements

I would like to thank Professor Quimby for his guidance and support during this project. I would also like to thank Siamak Ghorbani for help with using MATLAB. For her guidance and academic support I thank Professor Burnham. In regard to the late Professor Keil, his guidance and support will stay alive with me beyond this paper. For the moral support I have gotten from friends and family, I express my most sincere gratitude.

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1 Introduction

In the year 2012 there were over 1000 journal articles published that involved the use of optical tweezers. Optical tweezers are used for precision measurement and positioning of atoms, molecules, and even biological samples [1]. The 1997 Nobel prize in physics went to a group that developed methods to trap atoms with lasers [2]. Clearly the importance of optical trapping is well recognized in the scientific community.

An industry that is more familiar to the average person is fiber optic communication. The amount of internet traffic is on the order of 10's of exabytes a month [3]. This data is being delivered to billions of individuals through fiber optic cables. The amount of data that goes through the internet's infrastructure is only going to increase and developing methods to alleviate and prevent bandwidth issues are important to society as a whole. Current methods for increasing the bandwidth for optical fibers are frequency-division multiplexing, wavelength-division multiplexing, and polarization multiplexing [4].

Using light with orbital angular momentum is a possible technique that can be applied to both optical trapping as well as fiber optics. Orbital angular momentum (OAM) states of light carry discrete amounts of orbital angular momentum which can be transferred to other systems per conservation of momentum. This momentum transfer is part of the reason why OAM states are an ideal option for creating optical traps. Another feature of OAM states is that they are optical vortices. Optical vortices contain a screw dislocation meaning they have zero intensity in their center. The radius of this dark circle varies based on the topological charge of the vortex state. The charge is analogous to quantum numbers in quantum mechanics in that it is discretized and describes the state of the vortex. A major benefit of the zero-intensity singularity is that it allows for the system being trapped to have zero or almost zero light intensity on it. This is a benefit for sensitive systems that should not have a high intensity beam shining on it.

Fiber optic communication benefits from using OAM states because of the possibility of OAM multiplexing. Similar to a quantum mechanical system consisting of several energy

states with different quantum numbers, an optical waveguide could contain multiple OAM states with the different states encoding additional data than a typical fiber mode would be able to. One difficulty with using OAM light in optical fibers is preserving the state of the mode. OAM modes tend to couple with other, unwanted modes. Once this happens the OAM mode is irretrievable.

This project investigates the creation of optical vortices using holograms. Holographic interference has been shown before to be a straightforward method of creating OAM states of light. Holograms also allow for a lot of flexibility in the OAM states created. The quality of the holograms was tested as well as the quality of the vortices produced by them. This quality control is important for any future groups to ensure that their data is reliable. Once created, the vortices were characterized by their intensity profiles. The effects of coupling the vortices into an optical fiber were also investigated. The use of optical fibers to propagate OAM states is crucial to having either optical trapping or OAM multiplexing to work successfully.

2 Literature Review

The study of light with orbital angular momentum requires some knowledge of optics. The best place to start is with how light in general propagates. Light is composed of an electric and a magnetic field, \vec{E} and \vec{B} respectively. These fields are always perpendicular to each other. The cross product of these fields is the Poynting vector which is in the direction of propagation. There are many possibilities for the way light propagates such as in a simple plane wave. Alternatively, if light is circularly polarized then the electric field vector rotates around the axis of propagation. This is shown in Figure 2.1.

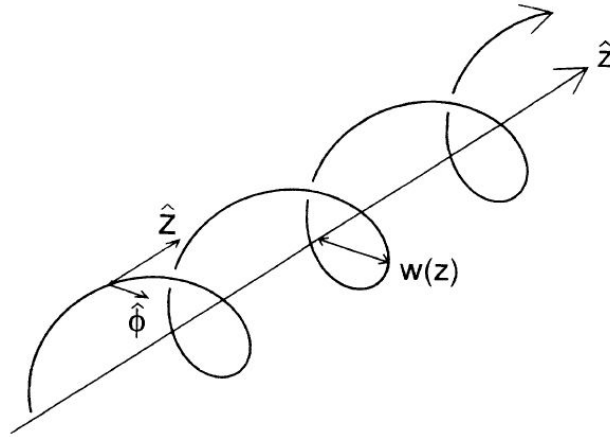


Figure 2.1: The Poynting vector for a circularly polarized electromagnetic wave

More complex functions of the Poynting vector are possible which result in different modes of light. Understanding optical modes allows one to explain more about light propagation than the Poynting vector offers.

2.1 Mode Theory

The concept of a mode in physics is somewhat abstract. The idea is that there are stable configurations of a system and unstable configurations. In optics, modes are light distribution patterns that remain stable as they propagate. A physical analogy is if you take a piece of string and tie one end to a pole. It is possible to take the other end and shake the string such that it maintains a consistent pattern. Shaking the string at another frequency or

inconsistently will obviously still move the string but it will not be in any recognizable pattern. By having light in a mode it can propagate great distances in an optical fiber and still behave the same (be in the same pattern) as when it went into the fiber.

2.2 Waveguides

A waveguide does exactly what the name implies, it guides waves. The principle behind this is total internal reflection. In general, when light hits a boundary, part of it reflects back into the medium it came from and part of it refracts at an angle into the new medium. In Figure 2.2 we can clearly see how when light goes into a more optically dense material, meaning the index of refraction is larger, we have the light bend towards the normal of the boundary. When light goes from a greater value of n to a smaller one, the light bends away from the normal. This is in accordance with Snell's Law,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2.$$

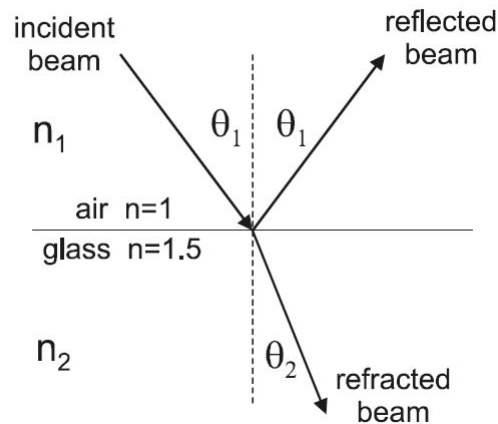


Figure 2.2: When light hits a boundary, part of it is reflected and part is refracted according to Snell's Law [5].

Although Snell's Law appears very simple, it leads to several interesting phenomena. If $n_2 < n_1$ then $\theta_2 > \theta_1$. It is clear that there is a limit on the range for θ_2 . When $\theta_2 = 90^\circ$

we call θ_1 the critical angle, θ_c . When $\theta_1 > \theta_c$ the light is totally internally reflected, as if the light hit a perfectly lossless mirror. Under certain conditions there can be repeated total internal reflection, shown in Figure 2.3. Depending on the angle of the light as it enters the waveguide, some light may escape into the outer layer, called the cladding. A simple example of two parallel glass plates shows how light can reflect several times and is guided along one direction. In the case of parallel plates, the waveguide would have a rectangular cross section and would therefore be called a rectangular waveguide. The naming convention for a circular waveguide is likewise because of its cross section.

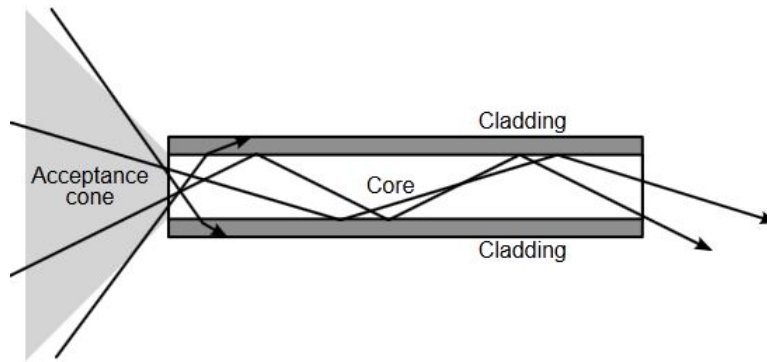


Figure 2.3: The core has an index of refraction n_1 which is larger than n_2 , the index of refraction in the cladding. This causes the light to be totally reflected multiple times [6].

2.3 Holograms and Diffraction Theory

One of the most well-known characteristics of waves is that they diffract. Diffraction is employed in holography when light diffracts through a holographic transparency to create an image. An understanding of diffraction allows one to appreciate the subtleties of how a hologram works.

2.3.1 Diffraction

Waves diffract when passing through a small opening or when bending around an object. A common example is Young's double slit experiment where a coherent wave passes through two small openings. The wave diffracts as it passes through the openings and creates a

diffraction pattern. This diffraction pattern is also called an interference pattern because the two new waves are interfering as shown in Figure 2.4. An extension of Young's experiment

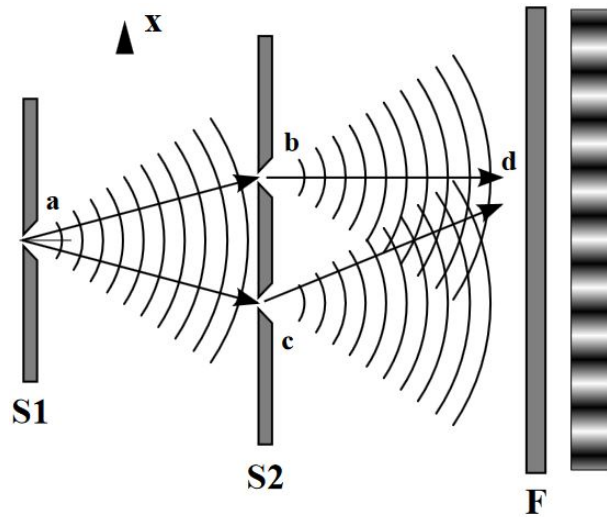


Figure 2.4: Image showing the diffraction of waves in Young's double slit experiment. Image from Wikipedia [7].

is a diffraction grating. A diffraction grating is a series of openings which is able to create a variety of interference patterns. The interference pattern consists of a series of bright and dark spots. Depending on the diffraction grating there may be an overall envelope function which causes the interference pattern to vary in a sinusoidal manner in addition to the alternating bright and dark spots.

2.3.2 Holograms

A hologram is a record of wavefronts. This record is created by the interference of a reference wave and an object wave. By subjecting the hologram to the reference wave the object wave is recreated. A major difference between a hologram and a typical picture taken using a film camera is that the film camera only records the relative light intensity but a hologram, assuming highly coherent reference and object waves, is able to record the intensity and the phase of the waves [8]. Holograms are able to recreate three-dimensional objects because they record the phase. There are a variety of types of holograms that create either 2D or

3D images, are in the near or far field, or have other effects in them. Of special interest to this paper are Fraunhofer holograms. These holograms are recordings of the far-field plane and a coherent background [9]. In the paraxial approximation, when the source and the observation point are near the optical axis, the hologram is a Fourier-transform hologram. A Fourier transform hologram records the interference of two waves whose complex amplitudes at the hologram are the Fourier transforms of both the object and reference source [8]. A more mathematically rigorous definition of Fourier holograms can be found in Collier [8] and it may be helpful to use Powers [10] or Strauss [11] for information on Fourier transforms.

2.4 Orbital Angular Momentum(OAM) light

2.4.1 What does it mean for light to have orbital angular momentum?

The momentum found in electromagnetic radiation has two components, spin angular momentum and orbital angular momentum. The spin is associated with the polarization of the wave while the orbital part is related to the spatial distribution [12]. Allen demonstrated that a Laguerre-Gaussian mode has an orbital angular momentum of $l\hbar$ for each photon. The variable l is the azimuthal mode index. The different modes carry different amounts of orbital angular momentum. Laguerre-Gaussian beams carry well defined orbital angular momentum but all physically realizable laser beams are expected to have, albeit poorly defined, orbital angular momentum. These modes may contain simultaneously $+l$ and $-l$ components which means that on average there is no orbital angular momentum.

Depending on the background of the researcher and purposes for researching OAM light they may refer to it in different ways. The optical vortices or wave front dislocations characteristic of the modes of light are analogous to vortices found in fluid mechanics. As can be seen in Figure 2.5 there is a dark spot in the center of the circle. It is an $l = 1$ mode and the dark spot is a singularity where the phase is not defined. There are simultaneously points with the phase ϕ and $\phi + \pi$ and the result is destructive interference from these phase differences [13].

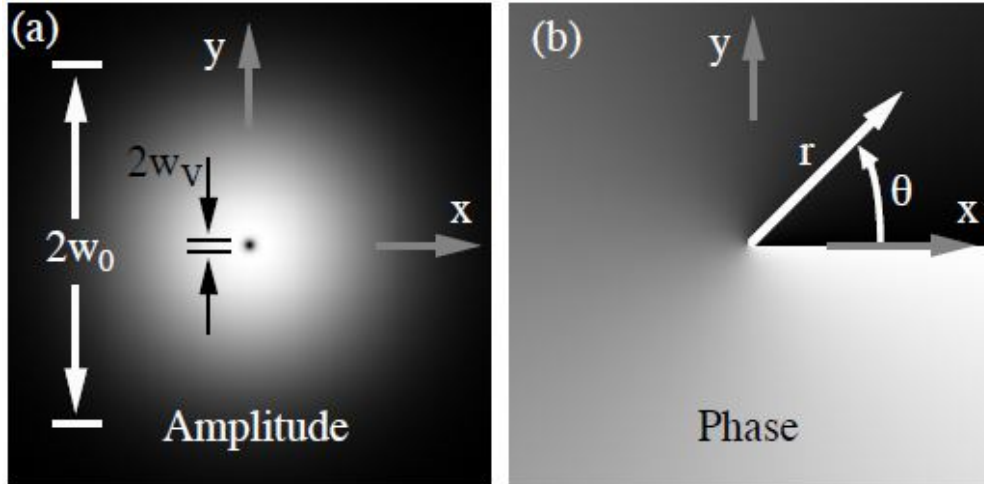


Figure 2.5: Intensity and phase profile of an optical vortex beam. The topological charge is 1. (a) The intensity of the light goes to 0 in the center and outwards at a radius w_v . The beam radius is w_0 . (b) The phase of the same beam is shown with black meaning a phase of 0 and white is 2π [13].

2.5 Ways to Create EM Waves with non-zero OAM

There are a variety of ways to create light that has orbital angular momentum. The process is typically done by altering a laser beam. Most lasers produce (approximately) either Gaussian or plane waves. An azimuthally dependent phase shift is then imparted on this beam. In principle a laser could be constructed to produce a beam with perhaps a topological charge of 1 but it would be difficult and costly to do so because the laser cavity would need to be tuned to do so. It is considered easier to modify the beam from a more common laser such as a HeNe laser than attempt to create a new type of laser.

One common method is to use a lens or phase plate system. One method uses an astigmatic lens converter where one lens introduces an astigmatism into the beam so that the focal length varies. A second lens counters this astigmatism [14]. A method using a single cylindrical lens has also been successfully done [14]. Alternatively a phase plate can be used to vary the path length that the beam follows. Both of these methods impart a varying phase change to the beam. The phase shift introduced is similar to that made in figure 2.5.

These methods have a variety of benefits and issues. They all are successful at making light beams that contain orbital angular momentum. There are some technicalities that must be addressed such as the effect of the Gouy phase shift on the phase of the vortex state. A Gouy phase shift occurs when the beam passes through the focal point and introduces a shift of π . A constant limitation with these methods is that they do not allow for multiple orders or modes with different topological charges to be produced at the same time. In the case of using a phase plate the order is not even known until further analysis is done unless accurate measurements of the optical path length difference are done [15]. It would be convenient if multiple orders could be created at the same time and the orders could be predicted before the experiment is started.

Holography can be used to create OAM light. Since holograms preserve phase as well as amplitude they are an excellent choice for creating light beams with orbital angular momentum. The idea behind using a hologram to create the OAM states is that the interference pattern of a laser beam and an OAM state is put on a hologram, and then when it is illuminated by a laser beam, the OAM state will be recreated.

The most important part of the holographic technique is the holographic pattern. The hologram may be constructed as if the vortex state was interfered with a plane wave [16] or a Gaussian wave [15] or directly from the use of Laguerre polynomials [17]. All of these methods work and create very similar holographic patterns but are dependent on the laser that will be used in conjunction with the hologram and also some are more mathematically involved.

Holograms, as opposed to the techniques using lenses or phase plates, have limitations with regard to resolution and the material used. The most cost effective method is to use a slide transparency [15] while higher quality beams can be produced using lithography [13]. One of the benefits of using the holographic method is the control over the characteristics of the hologram such as the charge of the vortex.

3 Methods

3.1 Construction of Holograms

The holograms used in this experiment were made by plotting the intensity distribution of the interference pattern of a tilted plane wave and an optical vortex [15]. The idea here is that a plane wave can be interfered with the finished hologram to recreate the optical vortices. The general form of a plane wave is $\psi = Ae^{ikx}$ but the plane wave used to make the hologram is traveling at an angle with the direction of propagation. This tilt angle has several effects that will be discussed in the results section. The other wave is an optical vortex. The simple case of just a plane wave with an embedded phase shift is

$$E(r, \theta, z) = E_0 \exp(il\theta) \exp(-ikz). \quad (3.1)$$

By squaring the sum of the amplitude function for an oblique plane wave, $u = \exp(-ik_x x - ik_z z)$, and equation 3.1 the result is the intensity distribution for the interference of a *tilted* plane wave and an optical vortex or

$$I = 1 + E_0^2 + 2E_0 \cos(k_x x - l\theta). \quad (3.2)$$

Rewriting equation 3.2 gives

$$T(r, \theta) = T_0 \exp \left[i\alpha \cos(l\theta - \frac{2\pi}{\Lambda} r \cos \theta) \right] \quad (3.3)$$

which is the transmittance of the beam and what was used to create the holograms. In equation 3.3 α is the amplitude of the phase modulation which was set to a constant value of 1 for all holograms. The charge or order of the mode is set by the value of l which will be an integer. The period of the line spacing on the hologram is set by Λ which is how the number of lines on the hologram is changed. T_0 is just the amplitude and was set to 1

since the precise value associated with each point in the hologram is not needed, just the relative value. The equation was graphed in MATLAB [18] with the code for doing so in Appendix A. An example of one of the holograms is shown in Figure 3.1. There is only one prong diverging from the vertical line to each side, creating a fork pattern.

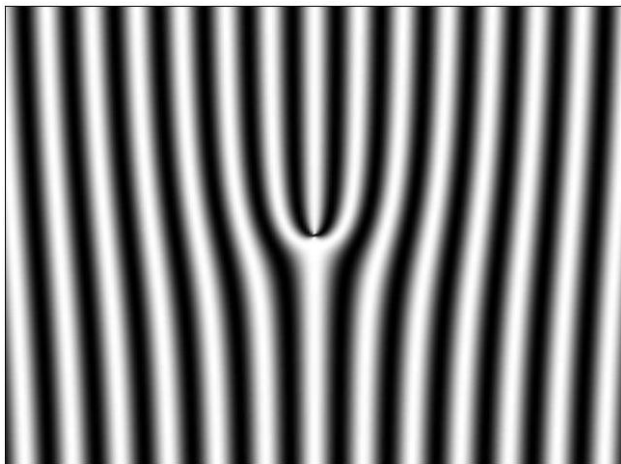


Figure 3.1: An example of a hologram with a topological charge of 1.

The process for creating the holograms starts with creating the image in MATLAB. From there a film camera was used to take a picture of the image. The camera was a Nikon N4004s and the film used was TRI-X 400. The camera was placed approximately 90cm from the computer screen showing the MATLAB figure. One goal when creating the holograms was to fit as many lines per mm onto the hologram as possible.

3.1.1 Estimation of Lines per mm on Holograms

An estimation for the number of lines that will be on the final hologram can be done by calling the distance from the computer screen to the lens of the camera, d_1 , and the distance from the lens to the film, d_2 . We can then find the relationship between the spacing on the computer screen, a , and the spacing on the film, b . This will enable us to end up with the final spacing of the diffraction pattern. We can define the angle θ as the angle formed by two lines in the interference pattern, assuming the lines to be perfectly parallel. We have two

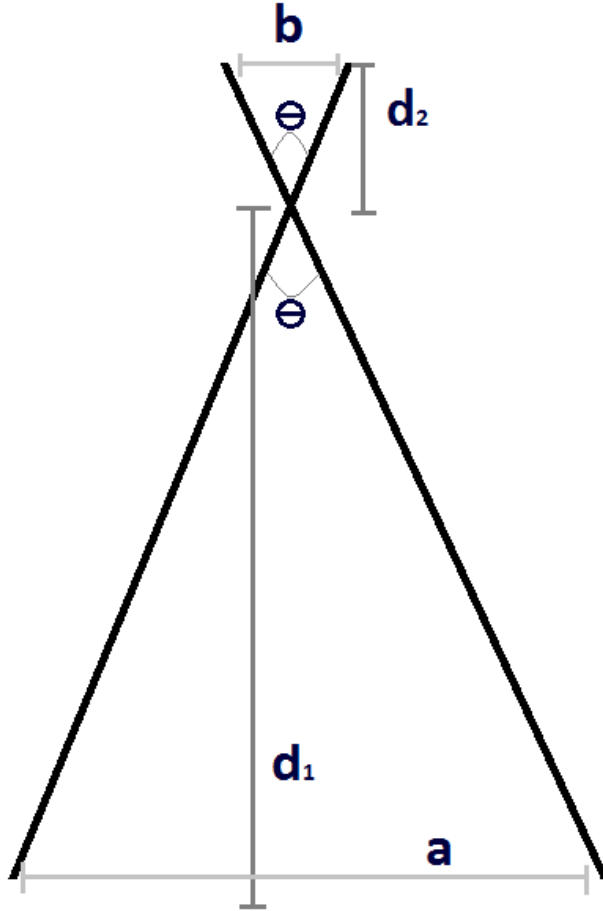


Figure 3.2: Diagram showing how to determine the number of lines that will be on the hologram.

isosceles triangles of height d_1 and d_2 . by the law of cosines we have

$$\cos(\theta) = \frac{4d_1^2 - a^2}{4d_1^2 + a^2}$$

and

$$\cos(\theta) = \frac{4d_2^2 - b^2}{4d_2^2 + b^2}.$$

When we set the equations equal to each other and simplify we get

$$b = a \frac{d_2}{d_1}.$$

Physical limitations means that d_2 is permanently fixed. It is approximately 10cm. The distance from the computer screen to the lens can vary but a length of 1m ensures none of the hologram is clipped off. The spacing, a , is therefore the most flexible parameter.

Although the value changes for each holographic pattern, a typical value of the spacing from peak to peak is approximately 2mm. That means that the spacing on the film negative, b , will be approximately 0.02 mm per line. Using ASA standard 135 film, we know the width of the negative is 36 mm which leads to 1800 lines on the negative.

3.1.2 Angle of Separation

The orders of the diffraction pattern must be sufficiently separated so that they can be observed visually as well as measured. For the lab space available an angular spacing of 0.05 rad will allow the diffraction pattern to be well spaced. This is because the beam will travel approximately 2m which for an angular spacing of 0.05 rad will have a spatial spacing of 10cm. That spacing is θ , λ is the wavelength, and d is the linear spacing on the film. The relationship between those three variables is

$$\theta = \frac{\lambda}{d}$$

or

$$d = \frac{\lambda}{\theta}.$$

By definition

$$d = \frac{1}{\text{lines per cm}}$$

So putting everything together and remembering we have a HeNe laser ($\lambda = .663\mu m$)

$$\theta = .663 \times 10^{-4} * \frac{\# \text{ of lines}}{1 \text{ cm}}$$

so in order to have $\theta = 5 \times 10^{-2}$ rad we must have 754 lines per cm. Compared to the previous

section with 1800 lines per 36mm or 500 lines per cm it would seem that the method described to create the holograms is inadequate. The measurements are conservative estimates and in reality the line spacing on the negatives could be more than twice as dense. Additionally the negatives can be shrunk on the computer screen, effectively reducing the length of 36mm to approximately 20mm and increasing the lines per cm to 900.

3.2 Holographic Interference

Once the film negatives were created the holograms could be used to create diffraction patterns. The holograms needed to be interfered with a plane wave. The plane wave was created by taking a HeNe laser of 633 nm wavelength and passing it through a 10X microscope objective with a numerical aperture of 0.25. At the focal point of the microscope objective a $25\mu\text{m}$ pinhole was placed to increase the spatial coherence. The light coming from the pinhole is now diverging and so a convex lens was used to collimate the beam into a good approximation of a plane wave as shown in figure 3.3. Now the interference of this plane wave with the hologram will recreate the optical vortices. This basic setup allows for the far-field diffraction pattern to be easily seen by the naked eye as seen in Figure 3.4 where each of the circles shown has a diameter of approximately 1.25cm

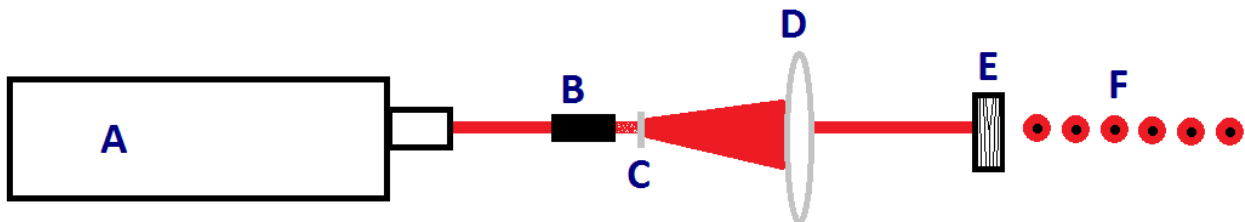


Figure 3.3: Schematic of experimental setup. A is the HeNe laser. B is the microscope objective. C is the pinhole. D is the converging lens. E is the hologram. F is the resulting beam consisting of optical vortices.

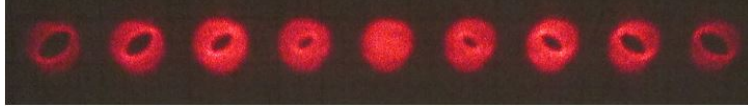


Figure 3.4: With basic equipment the diffraction pattern from one of the holograms can be easily seen.

3.3 Quality Control of Lab Setup

The validity of any data gathered should be able to be quantitatively justified. This was done in several ways. The first was to measure the spatial structure of the laser beam used for creating the diffraction pattern. This was done by having a pinhole several orders of magnitude smaller than the beam pass through the beam with a photodetector behind the pinhole. As the pinhole passes through the beam's diameter, if the beam is a plane wave, the intensity will instantaneously reach a constant maximum. Since it is impossible to have a real plane wave the best the laser could do is an approximation. The intensity of the beam was found to measure approximately as a plane wave with a constant intensity that quickly changes to or from zero at the beam's perimeter.

3.4 Intensity Profile of Diffraction Patterns

One of the primary methods for characterizing the orbital angular momentum modes is by characterizing the intensity patterns created by them. This was done by placing a pinhole with approximately a $500\mu\text{m}$ diameter directly in front of a photodetector. The pinhole is small enough that it can be treated as only allowing the intensity of individual points to be measured. Translating the photodetector and pinhole setup, from now on just called the photodetector, at a steady rate creates a linear scan across the diffraction pattern. By passing through the diameter of one of the modes a quantitative graph can be created which gives greater insight into the structure of the OAM modes.

3.5 Propagation of OAM Modes Through a Medium

It is expected that the modes may be perturbed in an optical fiber or when passing through some medium. The effects on the characteristics of the beam such as topological charge are of more importance since those properties must be preserved. The initial test before introducing any fibers is to see how the beam behaves when it is focused to a point and then collimated with a lens. The light would need to be focused for it to enter a fiber so this test checks to see if any irregularities are introduced. The beam was allowed to propagate approximately two meters so that each mode was sufficiently separated. Once the desired mode was isolated it passed through a converging lens of focal length 19cm and then through a second converging lens of focal length 7cm. The distance between the two lenses was 26cm so that the exiting light was collimated. A diagram of this setup is shown in Figure 3.5.

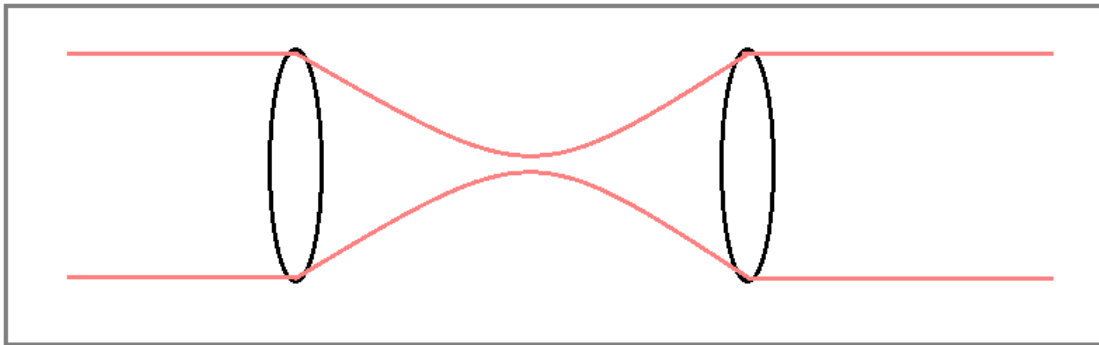


Figure 3.5: Diagram showing how the approximately collimated beam containing an OAM mode is focused to a point and then collimated again using a second converging lens.

The beam was also coupled into a highly multimode fiber. This plastic fiber was cut from a supply and the ends were smoothed using fine sandpaper. The fiber was placed so that the entrance of it was at the focal point of the focusing lens. The collimating lens was moved so that the end of the fiber was at the focus of the lens. The fiber was 2mm long. A diagram of this setup is shown in Figure 3.6.

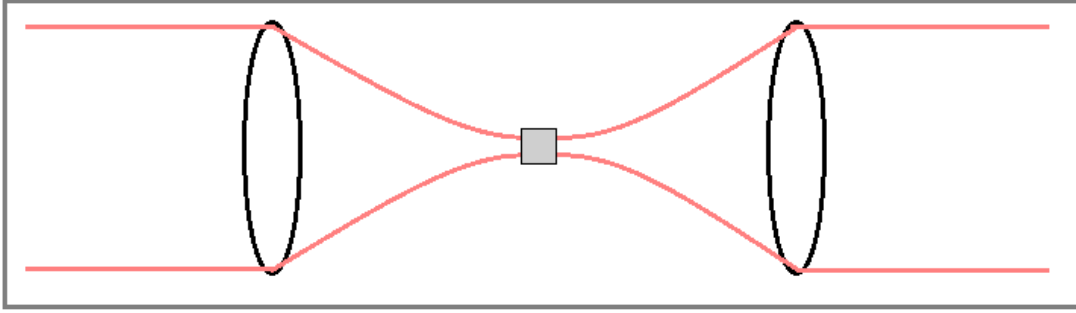


Figure 3.6: Diagram showing how the approximately collimated beam containing an OAM mode is focused to a point, coupled into a short fiber, and then collimated again using a second converging lens.

4 Results and Discussion

4.1 Results

One of the first goals of this project was to create holograms that were a recording of the interference pattern of a Laguerre-Gaussian function with a plane wave. It proved simpler and easier to scale to arbitrary topological charges to use the interference pattern of optical vortices with a plane wave. The resulting holograms matched holograms created in other works [16][15]. Several of the holograms created are shown below. The settings can be seen in Appendix B. Figure 4.1 shows examples of holograms used on the left with an enlarged version on the right. Hologram 7, Figure 4.1a and b, actually has $l = -1$ but was rotated 180° as if $l = 1$ to better show the changing pattern.

The holograms were successfully interfered with a HeNe laser beam to create optical vortices. A diffraction pattern was created from the hologram. This diffraction pattern was a series of optical vortices. These beams were of varying size and quality as shown in Appendix C. The vortices could be made arbitrarily large by allowing the diffraction pattern to propagate farther.

The OAM modes were found to be very sensitive to possible phase changes. The phase change imparted to the laser beam which creates the optical vortices is easily disturbed. The

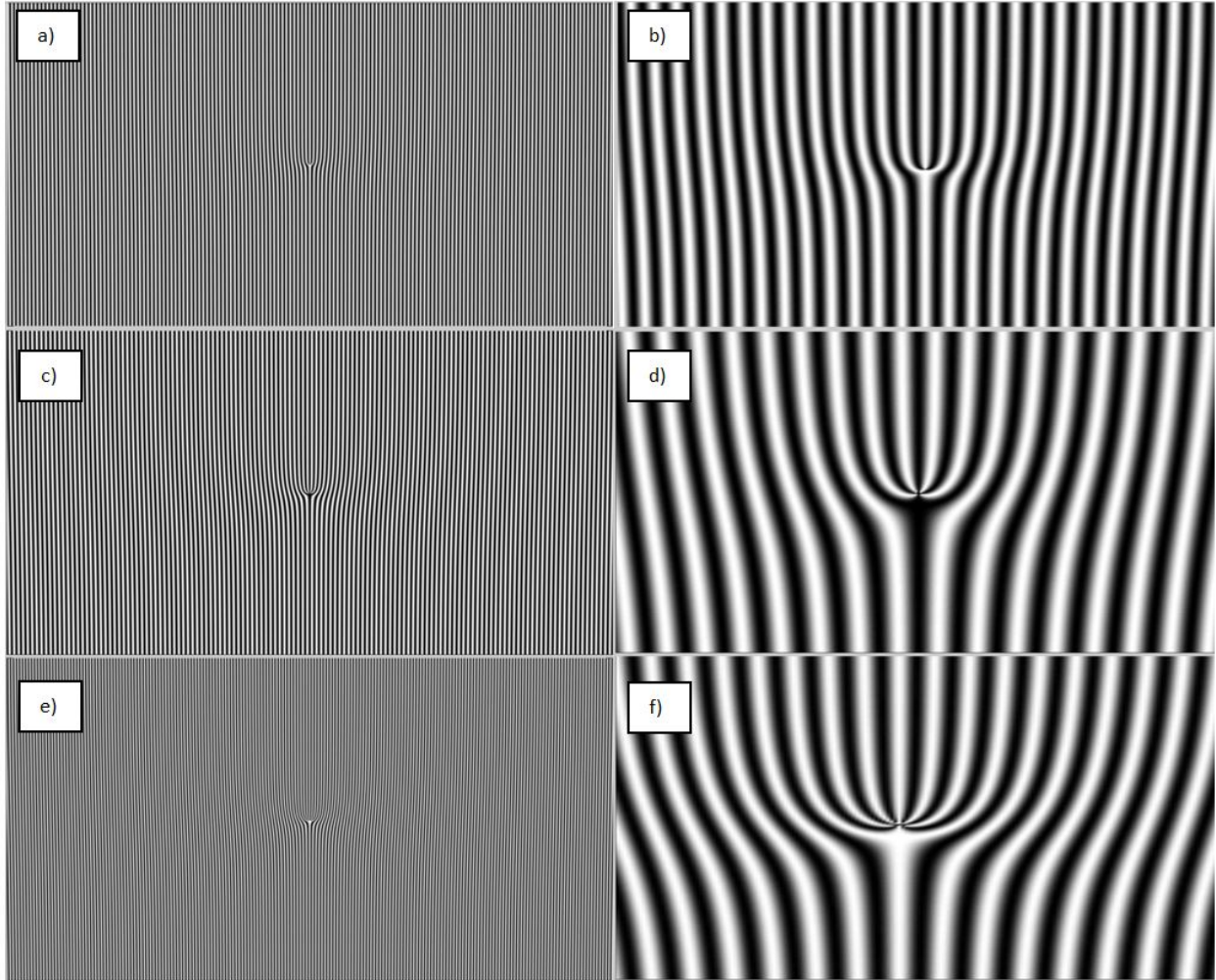


Figure 4.1: Examples of the holograms used. a) Actual scale of hologram 7. b) Enlarged version showing the fork pattern for slide 7. c) Hologram 6 with enlarged version in d). e) Hologram 23 with enlarged version in f).

natural curvature of the film negatives created distortions in the diffraction pattern. The correction for this is to use glass slides to press the negatives flat or use some other holder to get the same effect. A glass slide typically used for microscopy and therefore of high optical quality is still able to distort the vortices if placed between the hologram and the detecting screen.

4.1.1 Intensity Measurements of Optical Vortices

After visually confirming that the beams were able to propagate in free space, the intensity of the vortices was measured. By taking a series of point measurements across the vortices the intensity of the horizontal or vertical diameter could be accurately recorded. Figures 4.2, 4.3, and 4.4 shows some of the intensity patterns measured. The intensity of the optical vortex states should be symmetrical with two peaks for when a photo detector passes in to and out of the vortex. The singularity is expected to have no light meaning the intensity will be zero for the entire time the detector is within its radius. Some measurements of the intensity do not have a consistently dark inner circle as seen in Figure 4.3 while others behave nicely such as Figure 4.4.

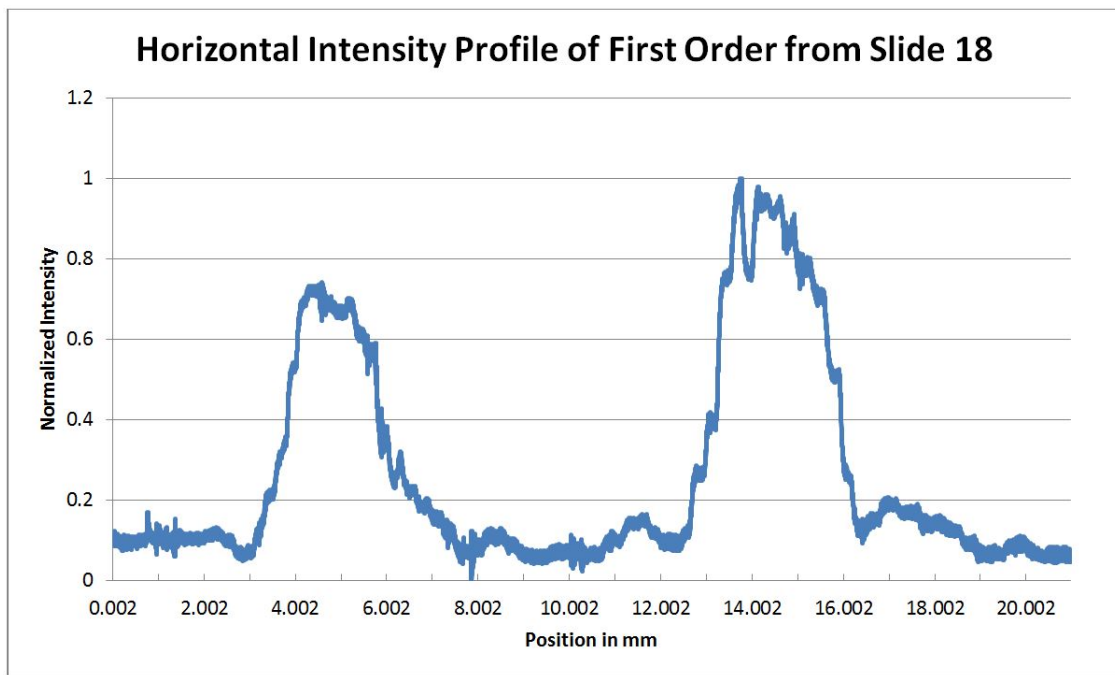


Figure 4.2: Shown is the intensity profile of the horizontal diameter for the first order of hologram 18. The path length from the hologram to the detector is approximately 4 meters.

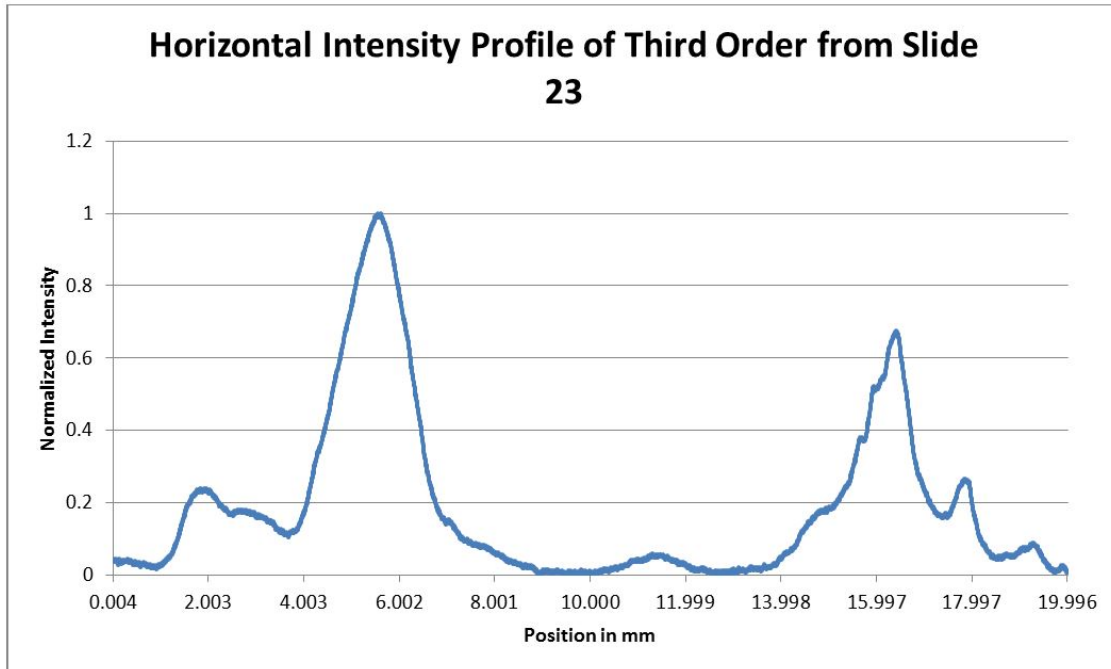


Figure 4.3: Shown is the normalized intensity profile for the third order of hologram 23. The path length from the hologram to the detector is approximately 4 meters.

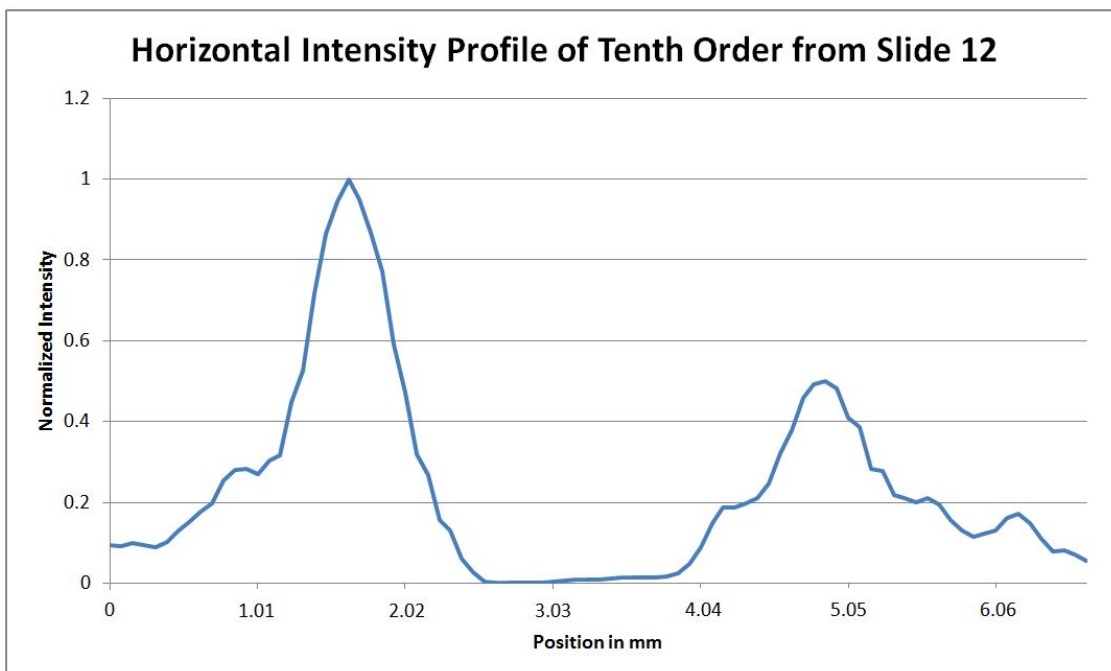


Figure 4.4: Shown is the normalized horizontal intensity profile for the tenth order of hologram 12. The path length from the hologram to the detector is approximately 2 meters.

4.1.2 Propagation of Optical Vortices

The optical vortex states were successful in propagating free space. Arbitrary distances up to several meters, limited by the size of the room, only increased the relative size of the vortices. The distance from the hologram and the radius of the optical vortices are directly proportional in the far field. No other features were seen to change in free space.

When the optical vortices were focused to a point to simulate coupling into an optical fiber the states did not deform or become degenerate after being focused and then collimated using a second lens. This shows that optical vortices are able to be put into optical fibers since any beam must be focused into a fiber and then collimated when exiting the fiber. An attempt was made to couple the optical vortices into multimode fibers. Individual vortex states were focused into fibers but the quality of the fibers were too low to have the vortices propagate in the fiber. Light visibly was exiting out of the sides of the fiber which means that the entrance to the fiber was too rough and did not allow the vortices to undergo total internal reflection. When the vortices exited the fiber there was a distorted vortex in the very near field which diffracted quickly and could not be collimated.

4.2 Discussion

Characterizing the behavior of optical vortices was one of the main goals of this project. By investigating the intensity of the vortices any defects can be quantitatively analyzed. Other effects can be qualitatively described so that a more complete idea of how optical vortices act can be established.

4.2.1 Intensity Profiles

Figures 4.2, 4.3, and 4.4 show a pattern of approaching the expected distribution of two symmetrical peaks with a zero intensity valley as the order of the optical vortex increases. The peaks become better defined and also the smaller secondary peaks that flank the far left and right of the graphs reduce in size as the order increases.

4.2.2 Undesirable Effects In Optical Vortices

The equation used to graph the holograms, Eq. 3.3, has the variable Λ which relates to the spacing on the film negative. The tilt of the incident plane wave and the spacing of the lines on the hologram are directly proportional with more lines on the negative appearing when the plane wave is at a larger angle with the normal to the plane. No correlation was found between the value of Λ and the tilting of the optical vortices in the diffraction pattern.

The tilt in the diffraction pattern is symmetrical along the horizontal and rotating the negative 180° also rotates the diffraction pattern which means it is caused by the hologram and not one of the pieces of optical equipment. There were two ways found to remove the unwanted tilt and have the vortices become circles instead of ellipses. The first was to have the beam striking the hologram be out of focus. This causes the beam to not be perfectly collimated. This was able to correct some of the tilt but is not ideal since it is inconsistent as to how much the lens should be moved so that it removes the tilting effect. The second method is to turn the hologram so that it is at an angle of approximately 45° to the incident laser beam. This method is a more reasonable approach because it simulates the conditions under which the holograms were created. The assumption when creating the holograms was that a plane wave was traveling at some angle to the normal of the hologram. The interfering plane wave should then be at an angle to the hologram. This then raises the question of why some of the holograms do *not* have the tilted elliptical pattern when the laser beam is perpendicular to the surface of hologram.

When the created optical vortices are well-made they will be easier to characterize. Experimentally it is difficult to measure the intensity profile of the vortex when it is not circular. Any modeling of the system is more difficult when the data is guaranteed to not fit. The diffraction pattern should be able to be modeled by taking the Fourier transform of the hologram. This model was not able to be completed for this paper but would have created a way to directly compare the experimentally created diffraction patterns with the theory.

4.2.3 Mode Propagation

Free space propagation is a simple task once the holograms are made. Similarly focusing the optical vortex to a point and then collimating the mode again is not difficult. Care was made to ensure that only one mode was being manipulated at a time. At the focal point of the the focusing lens the vortex appeared to look like any laser beam focused to a point, just a red dot. The near field pattern, close to the focus, did show the vortex states with their singularities.

Putting an optical vortex of any order, aside from the trivial case of 0, into an optical fiber is significant. The inability to collimate the beam from the fiber is most likely due to the quality of the fiber. It is easy to have irregularities on the surface of either end of the fiber. It is almost certain that the entrance of the fiber was too rough due to the fact that light was exiting the sides of the fiber instead of undergoing total internal reflection. There was some remnant of the circular mode after passing through the fiber in the near field. The beam quickly diverged and was not able to be collected by the second lens. It might be possible to use a converging lens with a focal length on the order of mm to collect the mode and collimate it. One possible way to do this would be to use a microscope objective.

The issue of fiber quality is very important for this experiment. A short fiber, several mm long, should act as a piece of glass when the mode passes through it. Since it is possible that even high quality glass can alter the phase of the mode, the method of smoothing the ends of the fiber must be carefully chosen. It is not expected that a typical multimode mode fiber will work over long distances but it is a good proof of concept in the short range.

5 Summary and Future Work

5.1 Summary

The project successfully created holograms that can be used to produce light with orbital angular momentum. These orbital angular momentum modes or optical vortices have the potential to be used in fiber optic communications and in the trapping of small molecules. Both of these applications will require the optical vortices to be carefully controlled and directed using optical fibers.

5.2 Future Work

Research into light with orbital angular momentum is still a new field. Areas of interest are in the creation of the optical vortices. Improvements to the resolution of the holograms as well as the technique used to create the graphs for them would be welcome. The largest challenge is creating optical fibers to transport the OAM modes. Theoretical and experimental work is being done to create novel fibers that preserve the OAM modes during propagation. An understanding of how the OAM act in free space and what to expect is critical for creating these new fibers.

There are a variety of methods for creating optical vortices. One of the advantages of using holograms is that multiple orders are produced at once. Additional work can be done to create arrays of optical vortices that consist of multiple vortices of possibly varying order in a grid as shown in [15]. Creating arrays of optical vortices may be beneficial for optical trapping of multiple molecules. It also may grant some insight into the behavior of OAM modes that is not as apparent in a linear selection of modes.

Mathematical modeling of the optical vortices was not able to be completed as hoped for this project. Modeling the expected intensity of individual modes allows for a quantitative comparison with the experimental intensity distribution. Models could be made for not just for a horizontal or linear diameter, which should be the same, but the entire vortex.

Being able to create models of the entire vortex which could be compared to the whole of an experimentally created vortex would be an excellent way to check the quality of the OAM mode. This brings up the next issue of possible improvements in laboratory equipment.

In an effort to reduce human error and gather more data, automatic data gathering would be a great improvement to this paper as well as future research. Having both the translation of the detector and the recording of the intensity (as a function of voltage) be done in a controlled and automated manner would allow for more accurate measurements of how the intensity varies over the diameter of the vortex. Alternatively there is equipment available that is able to measure the two dimensional intensity of a light pattern. Unfortunately the costs associated with such advanced equipment is prohibitive. Creative ways may be found to automate some of the repeat measurements in an inexpensive fashion. Being able to have a large volume of data will allow for any patterns in the defects in the optical vortices to be better understood and corrected.

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Appendices

A MATLAB Code

The following is the code used in MATLAB version 2012a to create the holograms. It creates two figures of the same hologram but with the color inverted.

```
clear all
close all
clc
x = -1000: 5 : 1000; % a row-vector of points for the x-axis
y = -1000 : 5 : 1000; % a row-vector of points for the y-axis
[X,Y] = meshgrid(x,y); % create matrices for grids of X and Y
T_0 = 1;
alpha = 1; %amplitude of the phase modulation
l = 1; %topological charge
bigdelta = 1000; %controls the period of the grating (fringe spacing)
G = bigdelta;
[M,N] = size(X);
for m=1:M
for n=1:N
q = atan2(Y(m,n),X(m,n));
r = sqrt(Y(m,n)^2 + X(m,n)^2);
T(m,n) = T_0*exp(alpha*l*cos(l*q - (2*pi*r*cos(q))/G));
end
end
Treal = real(T);
temp_colormap = colormap('gray');
```

```
my_colormap = 1 - temp_colormap;
pcolor(X,Y,Treal)% , axis('off')
colormap(my_colormap)
shading interp %(removes the grid)
figure();
pcolor(X,Y,Treal)% , axis('off')
colormap('gray')
shading interp %(removes the grid)
title('Original');
```

B Details for Holograms Created

The holograms were made using a variety of possible values for the variables shown in Appendix A

Picture ▾	L ▾	delta ▾	Binary ▾	Quality ▾
1	0	150	yes	2
2	0	150	no	2
3	1	150	no	2
4	1	140	yes	3
5	2	150	no	2
6	2	150	no	1
7	-1	130	no	3
8	-1	130	no	3
9	1	20	no	3
10	1	50	no	2
11	1	50	yes	2
12	10	80	no	1
13	1	10	no	3
14	1	15	no	3
15	1	100	no	3
16	1	100	yes	3
17	2	100	no	1
18	2	500	no	2
19	2	500	yes	2
20	0	50	no	2
21	0	50	no	2
22	-1	50	no	2
23	3	100	no	1
24	3	100	yes	1

C Diffraction Pattern of Holograms

Show below are the diffraction patterns for some of the holograms. From top to bottom it shows holograms 1, 5, 6, 8, 10, 12, 15 17, 18,19.

