UTILIZING A 4-F FOURIER OPTICAL SYSTEM TO LEARN MORE ABOUT IMAGE FILTERING

Author:
Corrado Ballaera
Research Conducted By:
Jaylond Cotten-Martin and Corrado Ballaera

Faculty Sponsor:
Romulo Ochoa,
Department of Physics

ABSTRACT

Spatial light modulators in conjunction with a 4-f Fourier Optical System provide a versatile way to study images and how they appear when modified with optical filters. We sought to develop a technique that utilizes the 4-f System to apply filtering in an efficient manner. We then compared our results to computer modeling software from Mathematica (Wolfram Research, Inc.) and MATLAB (The Math Works, Inc.). We were successful in developing our technique and our experimental models correlated well with the theoretical models.

INTRODUCTION

Video projectors are ubiquitous in today's classrooms and offices, but unbeknownst to most, they contain powerful optical-electronic hardware that can be used for manipulating light. One important piece of hardware within the projector is a spatial light modulator (SLM). An SLM is an optical device that allows for the manipulation of the spatial profile of a light beam to take the form of an image that the user desires. Most projectors contain three SLMs (blue, green and red) that, when illuminated with a white light source, creates the desired image. Many commercial SLMs are rather expensive, so utilizing them within a projector is a cost effective way to conduct experiments. By connecting a computer to a projector using a VGA cable, we can display images onto the SLM in order to further view and manipulate. For our purposes, we set up a 4-f optical system in order to analyze the properties of various images. The setup can Fourier Transform our images onto a "Fourier plane" where we can apply various filters and then inversely Transform our image in order to study how the image is modified. The experimental results after filtering was applied were compared to results from computer models. Learning how to manipulate the spatial profile of light and understanding how spatial filtering affects an image prove useful in many areas including Optical Tweezers and facial recognition software.

       Throughout this paper, we will discuss what Fourier Transforms are, what a 4-f optical system is and how an SLM combined with this system operates. Then we will explain the setup of the system and our experimental method. We will examine our results and findings while highlighting findings of interest. Last, we will summarize what we have done as well as discussing future work and applications.

THEORETICAL BACKGROUND

Electromagnetic waves and sound waves are just a few of the many things in this world that can be described as a wave. According to Fourier Transform theory, any wave is actually a summation of many different waves of varying frequencies. The Fourier Transform is a significant mathematical tool that helps to physically show which component waves construct a periodic or a non-periodic function. These component waves can further be displayed in what is called the frequency domain. Most people are familiar with a time-domain graph, which highlights how a wave changes over time, and can be displayed as a traditional sinusoid function. However, the frequency domain is a graph that plots the wave characteristics as a

function of amplitude versus frequency for a broad range of frequencies. The frequency domain allows for easier analysis of a wave's frequencies and amplitudes (National Instruments 2012).
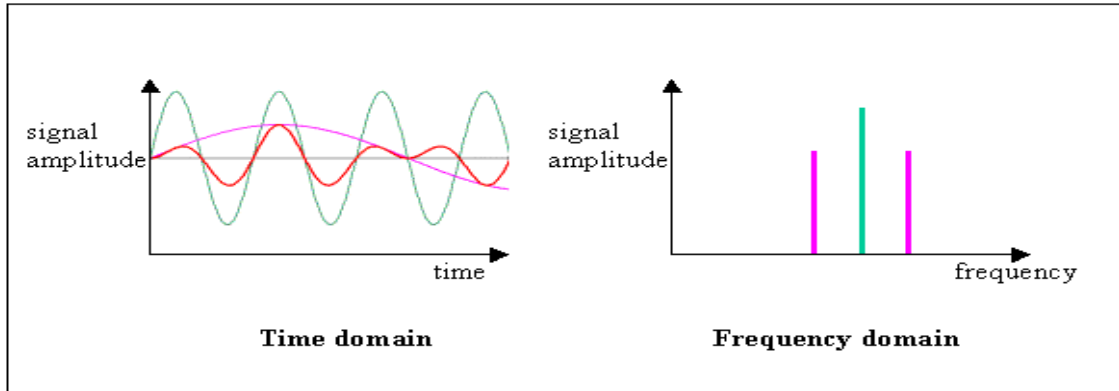

Figure 1. Image of the Time Domain vs. Frequency Domain (National Instruments 2012)

An image or photo is comprised of various spatial frequencies. Spatial frequencies are simply the frequency across space with which its brightness varies (Lehar). The frequencies can be represented in the frequency domain to better understand how they add to produce the resulting image. To do this, we are able to use a biconvex lens as a means to Fourier Transform our physical image. If an object is placed at the focal point of a lens, the light rays that radiate outward and hit the lens are emitted as a parallel beam. This parallel beam interferes with itself both constructively and destructively and the Fourier Transform is observed in the frequency domain at the distance of the lens' focal length from the lens. The inverse is also true that rays traveling parallel from a distance of the lens's focal length will be focused on the other side of the lens at the distance of one focal length.

The optical system we set up in order to study images is called a 4-f Fourier Optical System. The system is set up such that an object is illuminated one focal length in front of a biconvex lens. The image is Fourier Transformed one focal length behind the lens. This point is labeled as the Fourier plane due to the Fourier Transform being represented here. It is also here that we are able to apply certain filters in order to modify the image and study it. A low-pass and a high-pass are two filters to note. A low-pass filter lets lower frequencies pass through and blocks higher frequencies from passing through. A high-pass filter is the inverse of this, allowing higher frequencies through and blocking lower frequencies. From the Fourier plane, light travels parallel for a distance of one focal length until it hits a second lens with the same focal length as the first. This lens inversely Fourier Transforms the image, returning the light back to an image from the spatial frequency domain, and is focused one focal length behind the second lens. The resulting image can be observed and further analyzed. Effectively, light from the object to the resulting, modified image travels a distance of 4 times the focal length of the lens. This is the reason why the system has its name.

The object that we used in this system is called a spatial light modulator, or SLM for short. An SLM is a liquid crystal display that contains a layer of polarizing liquid crystals in between two polarizers that modulate the intensity of transmitted light (Huang 2011). As light enters the SLM, the first polarizer horizontally polarizes it. As a voltage is applied to the liquid crystals, they are oriented in such a way that rotates the polarization of incoming light. The analyzer then vertically polarizes light. The SLM allows for an image to be uploaded onto its LCD screen from a computer source. As light passes through the SLM, the light will be modulated in such a way that it exits the SLM as the desired image. Using an SLM is an efficient and useful way to input into the 4-f optical system whatever image we wish to study.

EXPERIMENTAL SETUP AND PROCEDURE

For this project, we used a powerful HeNe laser as our light source and the Red SLM. We took apart an Epson projector in order to obtain and use the SLM. We used two cameras from PixeLink (PixeLINK) and their proprietary software to view the images. These cameras do not display color, so the resulting images were in grayscale. The Experimental Setup can be seen in both Figures below:
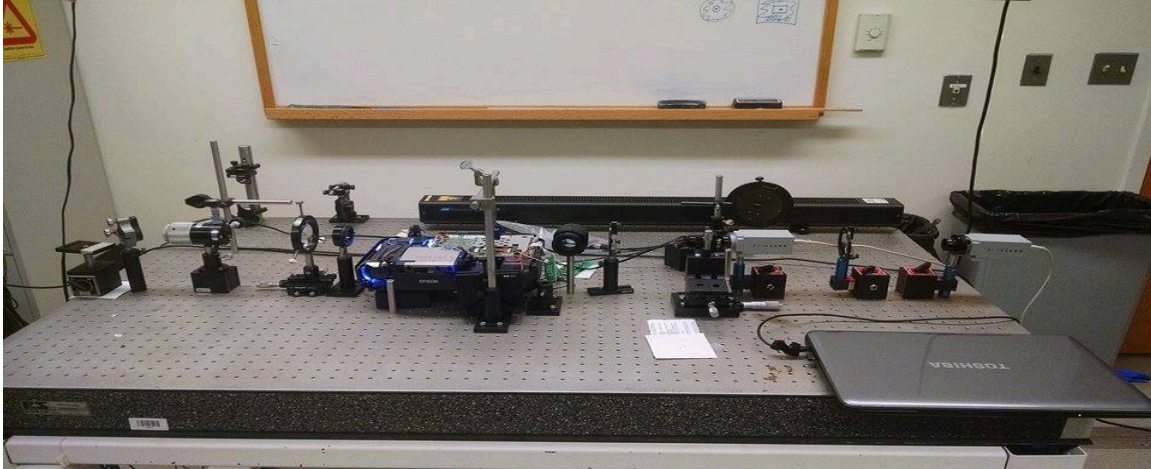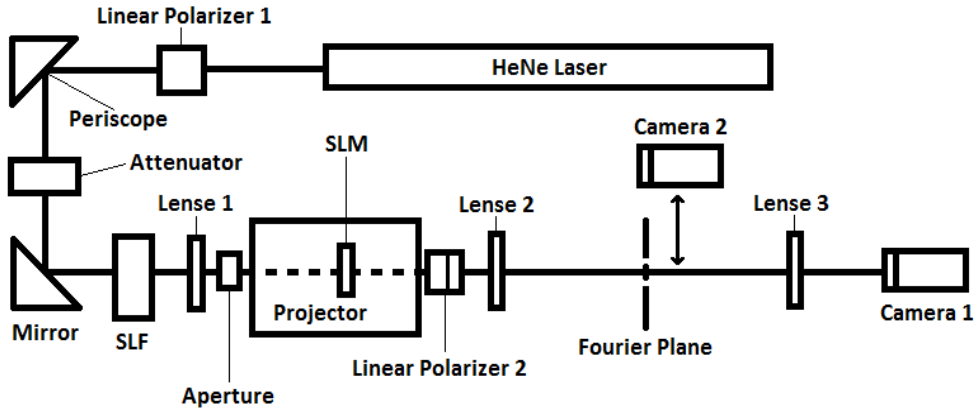

Figure 2: Experimental Setup of the 4f-Optical System

As seen in Figure 3, once the HeNe Laser is turned on, the light first passes through a linear calcite polarizer. This polarizer allows us to control the intensity of the laser by rotating it. This is useful if the image is too intense or too dim to view when picked up by the camera. The

Figure 3: Schematic of our Experimental Setup, listing each item used in our experiment

beam travels to the periscope, where it is redirected to a height that is more in line with the SLM later in the setup. Passing through the attenuator, the beam's intensity is once again lowered and then a mirror redirects the beam into a spatial light filter (SLF). This SLF is useful to "clean up" the beam; it removes aberrations in the beam that could have been caused by the other optical devices or by dust and dirt. The first lens helps to collimate the beam, which simply implies that the beam will not diverge much as it travels. The aperture helps to limit the radius of the laser beam that reaches the SLM so that it can be more focused onto it. At the SLM, an image that we wished to manipulate was uploaded from a computer through a VGA cable that plugged into the

back of the projector. The SLM was held in line with the beam by using a clamp. As the beam passes through the SLM, the light takes on the shape of the image. The light is subsequently polarized (reducing intensity) and sent through the second lens where the image is Fourier Transformed at the Fourier plane. It is here that we are able to apply various filters to alter the nature of the image. The light travels through the third lens where it is inversely Fourier Transformed into the camera lens of camera 1. The image that camera 1 picks up is sent to a separate computer where the modified image can finally be viewed using "PixeLink" software. As seen in Figure 3, there is also a second camera that we used. Camera 2 can move onto the Fourier plane in order to more accurately observe how the Fourier Transformation truly appeared.

Throughout the course of this project, we tested many different images and used various filters in order to modify them. We first tested simple images in order to get a sense of how the system worked. As seen in Figures 4 and 5, these simple images included those of alternating black and white lines and simple interference patterns to start.
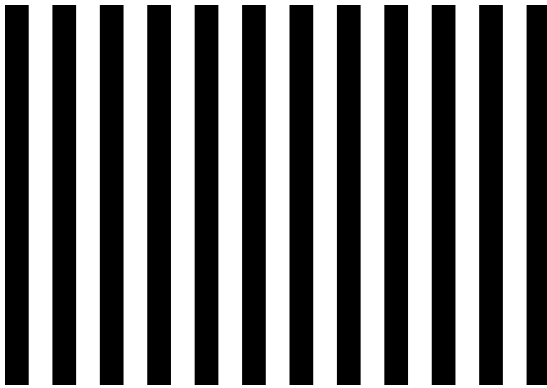

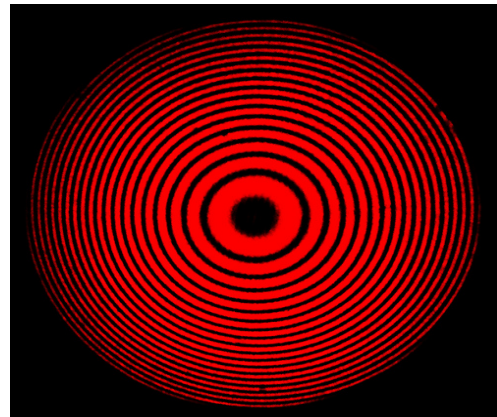Figure 4: Alternating Black and White Lines

Figure 5: Interference Pattern

We applied two general filters to these images- a low-pass and a high-pass filter. For our low-pass filter, we first created a pinhole in a Post-It note and attempted to hold it on the Fourier plane. This would allow more light in the center of the Fourier plane to pass through to the camera, but it proved troublesome to try and accurately put this into the correct position. For our high-pass filter, we used a transparent film and drew a circular dot with a sharpie marker. By holding this filter on the Fourier plane, we could block out light near the center of the Fourier Transform. This method proved effective in providing the correct filtering, but it was difficult to hold the filter in the correct position for an extended period of time since we did not mount the filters. To remedy this problem, we placed a micrometer mount (refer to Figure 2) on the Fourier plane and attached a clamp to it. This mount allowed for minor adjustments, micrometers in length, to correctly move our filters into position. We were able to clamp these filters to the micrometer mount, which made testing the images much easier. We then moved onto more complex images such as a Star Wars Stormtrooper and pictures of people by using the same method as described above.

Figure 5: Stormtrooper

We then attempted to test what would happen to images if we applied differently shaped filters to the Fourier plane. We decided to experiment with two more shapes: a triangle and a square. To do this for a high-pass filter, we drew a small triangle on a transparent film and a small square on another film. We put these on the Fourier plane and obtained different results.

To the naked eye, the Fourier plane appears to be a dot of light. We wanted to test if it looked any different upon closer inspection. To do this, we obtained camera 2 to place directly on the Fourier plane. This allowed us to capture novel images of what the complex Fourier plane truly looked like for each image. By knowing the content of the Fourier plane, we could even further improve our filtering techniques by determining precisely how much light from the Fourier plane to let through to camera 1. By using a camera iris as a filtering device, in conjunction with imaging of the Fourier plane from camera 2, we were able to develop an improved way of using a low-pass filter.

After we obtained experimental results from our optical system, we compared them to results obtained from computer models. To better understand how the Fourier plane should appear, we used MATLAB, as it provided to be a better model than Mathematica. We utilized its "fft2" function in order to Fourier Transform the images we uploaded to the software. However, in order to filter the images, Mathematica proved more useful. We were able to apply the low-pass and high-pass filter functions in Mathematica to understand if our experimental filtered images were accurate when compared to computer results.

DISCUSSION AND RESULTS

Our experimental results seem to correlate well with the computer models. For Figure 4, our Fourier plane results are shown below:
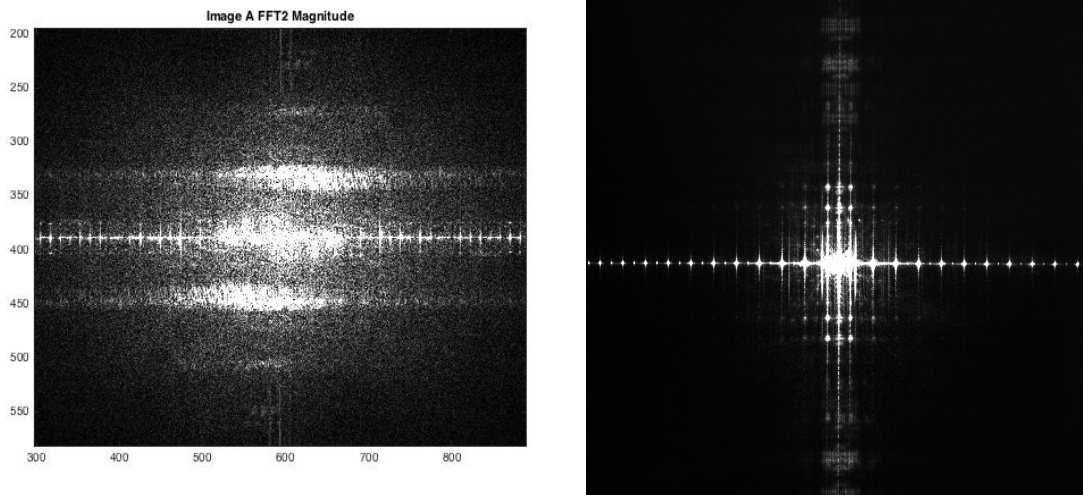
Figure 7: MATLAB Model of the Fourier Plane

Figure 8: Experimental Image of the Fourier Plane

As seen in the images, Figure 8 closely resembles Figure 7. There seems to be a bit of noise around the center of Figure 7, but all of the spatial frequencies can be seen and are equally represented in Figure 8. For all of the other images, the computer models are just as accurate in determining the Fourier plane. If we were to employ a low-pass filter to this image, we would let through light around the bright center point, effectively blocking the spatial frequencies more spread out from the center. To apply a high-pass filter, we would instead block this bright center point and let through the spatial frequencies located further from the center. Seeing the Fourier plane proves incredibly useful in accurately determining what part of the plane we would like to modify and filter. Through experimenting with variously shaped filters, such as a triangle or a square, we did not notice any difference in the resulting images than when we used a circular aperture or blockage.

What the Fourier planes actually look like seems to vary greatly between simple and/or circular images and more complex images like that of a Star Wars Stormtrooper or human. The differences in such images are shown below:
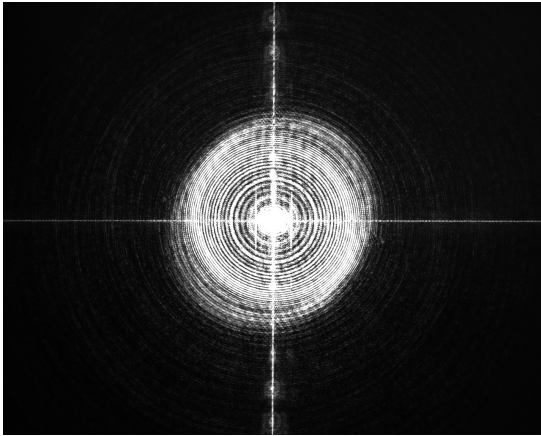
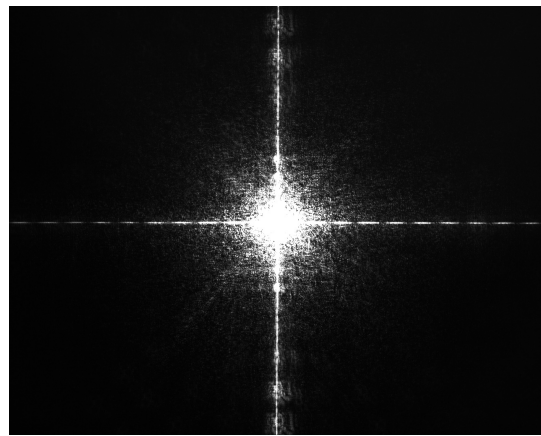Figure 9: Fourier Plane of Figure 5

Figure 10: Fourier Plane of Figure 6

Figure 9 seems to have a more complex Fourier plane. It has a bright center point, but travelling outward we observe circles centered about the middle. Figure 10 does not seem to share the same complexity. The image instead looks like a simple bright dot. This helps to show how images differ in the information they contain and how complex images seem to have their Fourier plane more concentrated near the center.

Applying filters to these Fourier planes results in noteworthy modified images:
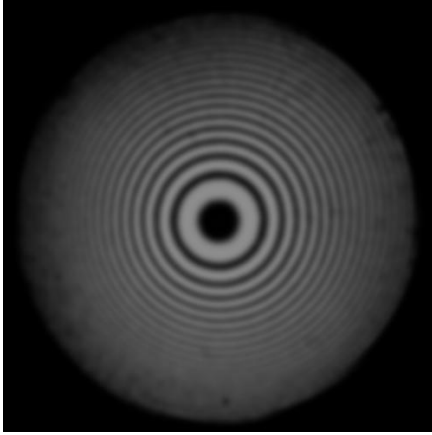
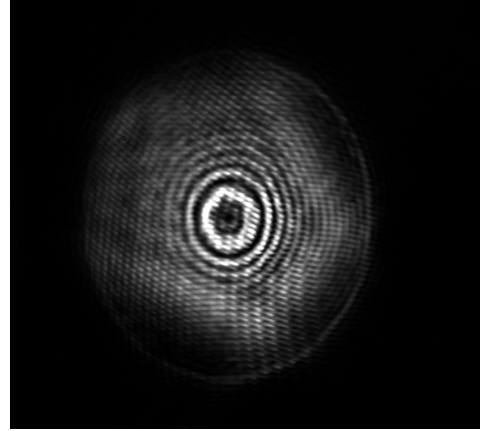Figure 11: Computer Model,
Low Pass Filter

Figure 12: Experimental Low
Pass Filter Using an Iris

These images are a low-pass filter of Figure 5. In the computer model, we see a blurring of the circles within the interference pattern. Near the center, the circles remain defined in their edges, but traveling outward, the image gradually loses distinction between circles and the image resembles more of a grey blur. For the experimental image, we used a camera iris and this resulted in a pentagonal-shaped view of the image. However, our experimental result is consistent with the computer model. We notice that near the center, the image retains brightness and it is easier to make out the circles. Transitioning away from the center, that distinction is lost. Both images are also blurred as a result of the filter.
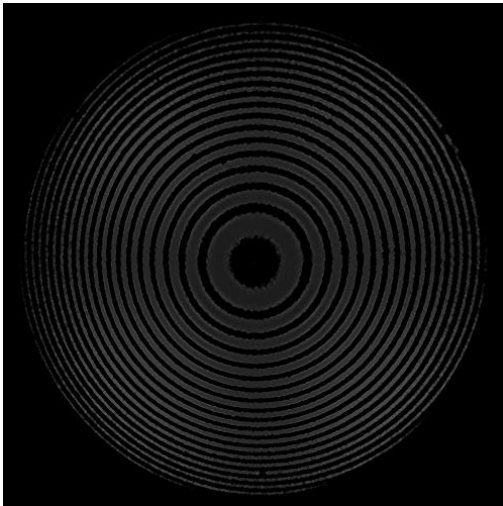

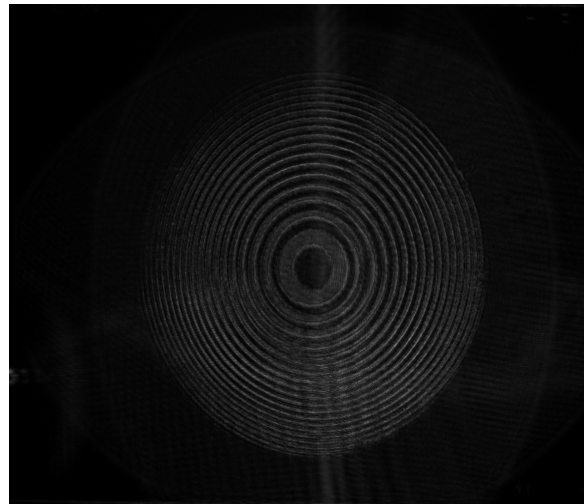Figure 13: Computer Model, High
Pass Filter

Figure 14: Experimental High Pass Filter

Both the computer model and the experimental result for the high-pass filter of Figure 5 are nearly identical. For both Figure 13 and 14, brightness is lost throughout the image. However, the circles of the interference pattern remain distinct. It is easy to see the edges of each circle from the center to the end of the image.

SUMMARY/CONCLUSION

This project proved to be successful in many ways. For one, we learned how to use a 4-f optical system in order to analyze and manipulate various images. We continually improved our technique of image filtering over the course of the semester by using a micrometer mount and using filters that, in conjunction with the image of the Fourier plane, can more accurately discriminate the amount of light we want to let through to the camera. We discovered which filters worked best for high-pass and low-pass so we could more efficiently utilize them. When compared to the computer models, we were successful in producing accurately filtered images. This was important for understanding how an image's information is gathered on the Fourier plane.

This work also helped to highlight how a low-pass filter and a high-pass filter modify images. A low-pass filter was found to blur the images, but left the brightness and the general image shape more intact. The edges of the images and finer details were not as distinguishable, however. With a high-pass filter, we found that the outlines of images, edges and details, were left more intact. However, brightness was lost and it became harder to understand what the image was.

In the future, we will use a second SLM as an even better filter at the Fourier plane. This way, we can create any desired filter much more precisely, which would allow for much more control. We want to learn more about beam reshaping by utilizing SLMs. If we can understand and accomplish beam reshaping, we would like to create an optical vortex that has applications in Optical Tweezers. An optical vortex can trap particles with light instead of merely pushing them, which is the traditional way that Optical Tweezers operate. This allows for enhanced precision when moving microscopic matter, which could greatly improve how objects are viewed under the microscope. With a better way to manipulate matter, more information can be gathered from microscopic images, therefore advancing discovery made about the microscopic world.

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