Creating Laguerre-Gaussian Modes using a Spatial Light Modulator

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Using a spatial light modulator (SLM) and a program designed in LabVIEW used to generate particular holograms, I show that various Laguerre-Gaussian (LG) modes are able to be produced. The ability to optically trap particles has major benefits in many areas of science, such as biology. Not only are small particles able to be optically trapped by light, but some applications allow for the particle to be rotated using angular momentum. In fact, a process called optical spanning can add or subtract orbital angular momentum (OAM) from a particle being optically tweezed using a different mode of light called the Laguerre-Gaussian mode. In order to produce this mode of light, a diffraction grating pattern (hologram) is used to change a Gaussian mode into this LG mode. This hologram is sent to the SLM's pixel screen, in which a laser beam is directed at and produces the LG modes through backscattering light.

I. INTRODUCTION

The idea of optical spanners spawn from optical tweezers, which were first created and explored in the early 1970s. Arthur Ashkin was one of the first physicists to explore and develop optical tweezers when he used the radiation pressure that light exerts to trap particles [1]. Using a diluted solution of 2.5-10 μm diameter latex sphere that were held in a glass cell constructed of microscope slides, Ashkin found that applying a few hundred milliwatts onto the sphere resulted in rapid motion [1]. Upon closer inspection, it was shown that if a particle was close the edge of the laser beam, the particle would be drawn to the beam's axis. Ashkin concluded that the light exerts scattering forces and gradient forces that guide the particle to the most intense part of the beam.

As optical tweezers became more studied, physicists began to wonder if different modes of light could be used to trap particles. In optical tweezers, a generic laser beam has a Gaussian profile that has the maximum intensity at its beam's axis as seen in Fig. 1. However, other such as Miles Padgett, thought it might be possible to induce different modes of light to optically trap dielectric particles. In February of 1996, Padgett along with N. B. Simpson and L. Allen published an article stating that they were able to "numerically model the axial trapping forces within optical tweezers arising from Laguerre-Gaussian laser modes" [2]. Using the LG mode, they were computationally able to model the transfer OAM to a trapped particle. Angular momentum is the sum of the OAM and spin angular momentum (SAM), both of which can be applied to trapped particles. OAM is produced using LG modes of light while circularly polarized light creates SAM. The technique of transferring OAM to trapped particles was then named as an optical spanner [2]. Then in August of that same year, the Padgett group along with K. Dholakia published an article measuring the OAM using optical tweezers with LG laser mode [3]. In this article, they were able to optically trap a particle in three dimensions and allowed it to rotate. Their results confirmed that SAM transfer is possible with circularly polarized light and OAM transfer is accomplished
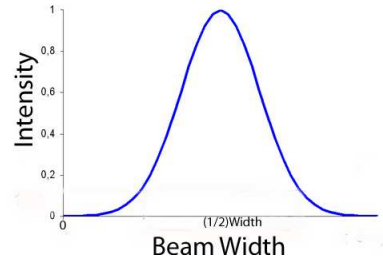

FIG. 1: The maximum intensity is obtain at the beam's axis or the radius of the beam.
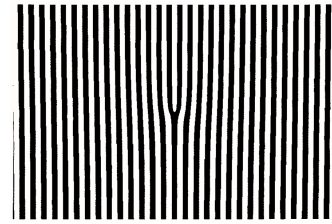

FIG. 2: This computer generated hologram diffracts beams with a plane wavefront into a beam with helical wavefronts. This image is from ref [7].

with LG modes. The photon spin of circular polarized light is known to be $\pm\hbar$. Cancellation of the rotation of a trapped particle under the effects of SAM and OAM was shown when a LG mode with an azimuthal index $l = 1$ produced OAM of $\hbar$ per photon[3]. This result confirmed that LG modes create OAM of $l\hbar$ per photon and that other modes of light can optically tweezer particles.

As mentioned before, many optical tweezers use a standard Gaussian profile to trap particles. An effective way to convert this Gaussian mode into a LG mode is to use computer generated holograms. In the past, these holograms have been printed on transparent paper with the laser being directed through the split (defect) as seen in Fig. 2. Each defect represents one azimuthal mode index of $l = 1$, such that two splits represents $l = 2$. In recent years, these holograms have been able to be calculated and used in a device called a spatial light modulator. A

SLM is composed of a twisted nematic liquid crystal display which is also combined with a spatial filter. Using a SLM, a laser beam is directed at the liquid crystal display and diffracted by the computer generated hologram. In order to control the display on the SLM, a recent method was develop that allowed for full spatial phase and amplitude control of a laser beam [4].

While most SLMs on the market are very expensive, a SLM (SDE1024 Spatial Light Modulator Kit) has been developed by Cambridge Correlators designed for educational research. A number of different scientists working in collaboration have developed software (in LabVIEW) that allows for control of SLMs. In their article, they state that "a major application of the program to be in optical tweezers to control the position, number, and type of optical traps" [5]. This program allows for the holograms needed to produce the LG modes of light to be calculated with ease. However, there is a trade off with this cheaper SLM as compared to the more expensive ones. This SLM does not have a perfect phase shift range of 2π, leading to loss of diffraction efficiency. This can eradicated however by optimizing this particular SLM to compensate for this imperfect phase shift range [6]. This particular SLM has been recently purchased by The College of Wooster in order to creating an optical spanner. By using the LabVIEW program provided by [5], I will computationally create the holograms needed for the SLM. Using these holograms, I will project them onto the SLM's display and direct a laser through the defect in order to transform the laser's Gaussian profile beam into various LG modes.

II. THEORY

Optical tweezers requires lasers with stable output and well defined intensity profiles. These profiles depend on the mode at which the lasers are operating at. In most optical tweezers, a circular cross section is used to provide maximum intensity along the beam axis and have a simple Gaussian profile [8]. However, if the laser operates in different modes of light, the maximum intensity for those profiles will no longer be in the beam's axis. For instance, the LG modes have circular cross-sections but lack any intensity in the beam's axis. This property of the LG mode produces a ring-shaped profile for the beam. These LG modes have helical wavefronts as opposed to planar wavefronts as shown in Fig. 3. The helical wavefronts are what give the LG mode a lack of intensity in the beam's axis.

There are many methods in which a Gaussian profile beam can be converted into LG modes. The program designed in ref. [5] allows for multiple techniques of computing holograms used for diffracting laser beams into different modes of light using an integrated interface. A laser beam can be represented by a complex field such as
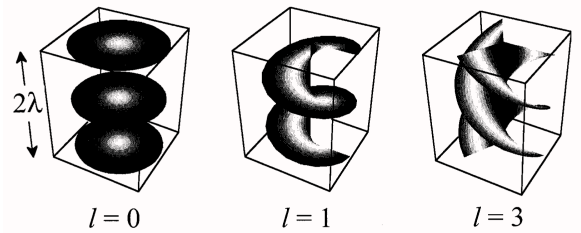
$$u = ae^{i\phi}, \qquad (1)$$

FIG. 3: These diagrams show the various wavefronts of laser beams with different azimuthal index numbers. The image on the left show a Hermite-Gaussian mode of light with planar wavefronts due the azimuthal index equaling zero. However, when the azimuthal index is greater than zero, then the wavefronts are helical due to $e^{il\phi}$ and become Laguerre-Gaussian modes. This image is from ref [7].

where a is the amplitude of the field and ϕ is the phase. SLMs have the ability to act as phase holograms, affecting the phase of the beam by a transmission of $t(x_h, y_h) = e^{i\phi_h(x_h,y_h)}$ [5]. Thus when a beam represent by Eq. 1 is directed at a SLM, the complex amplitude profile of the beam reflected off the SLM will be $u_h = ae^{i(\phi+\phi_h)}$, where ϕ_h is the phase of the hologram on the SLM. All the algorithms used in the designed program are able to generate desired phase patterns ϕ_h. A fact used in some of the design techniques is a Fourier transform relationship between the complex field u_h in the plane of the objective lens and the complex u_i at the focus of the lens in image space is

$$u_i(x_i, y_i) = \mathscr{F}\{u_h(x_h, y_h)\}, \qquad (2)$$

and thus the image space field is viewed as a scaled version of the far-field diffraction pattern leaving the SLM [5].

Of the algorithms available in this program, the gratings and lenses algorithm is the easiest and most suited for this experiment. The algorithm using the phase of basic optical components (gratings and lenses) to produce lateral and axial shifts. Suppose a beam with planar phase fronts is directed at a plane of the hologram (on the SLM) such that ϕ_h=constant, which is represented by a single focused spot in image space. Thus translating the spot laterally from the beam's axis corresponds to a beam striking a hologram plane that has an inclined phase front [5]. This is the equivalent to light passing through a small angle prism that linearly increases the phase delay ϕ_{prism} in the beam. This action can be represented as

$$\phi_{prism}(x_h, y_h) = a(\Delta x x_h + \Delta y y_h), \qquad (3)$$

where a is dependent on the wavelength and other imaging characteristics and $(\Delta x, \Delta y)$ is the physical lateral shift. The axial shift in image space is represented by

$$\phi_{lens}(x_h, y_h) = -\frac{k}{2f}(x_h^2 + y_h^2), \qquad (4)$$
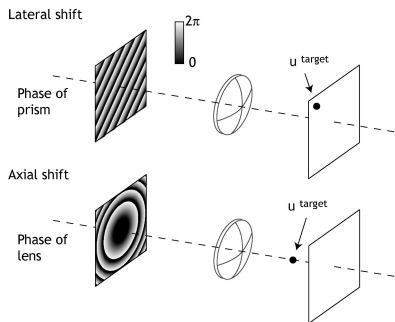
FIG. 4: This schematic shows the phase requirements to produce lateral and axial shifts for the grating and lenses algorithm. This image is from ref [5].

FIG. 5: The SDE1024 has a twisted nematic mode liquid crystal display screen in which the laser beam is directed at. The display screen visually produces the hologram needed to produce the LG modes.

where f is a function describing the axial shift distance (focal length) and k is the wave vector of the light [5]. These effects can be seen in Fig. 4. So if the target spot in image space is both axially and laterally shifted, then the phase of the hologram plane is the sum of ϕ_{prism} and ϕ_{lens} with mod2π, giving $\phi_h = (\phi_{prism} + \phi_{lens})\mathrm{mod}2\pi$. Using this method the grating and lenses algorithm automatically calculates these values of ϕ and then produces the corresponding hologram. The hologram is then shown on the SLM's display screen.

III. PROCEDURE

The SLM that was used in this experiment was the SDE1024 developed by Cambridge Correlators as seen in Fig. 5. The SLM has a twisted nematic mode liquid crystal display and operates at wavelengths of 430-650 nm. The SLM connected to the computer via VGA connector and acted as a second monitor in extended screen mode. In this way, images could be dragged onto the screen of the SLM. The program used for computing the holograms was the LabVIEW program that was designed in [5]. This program was downloaded from the Glasgow
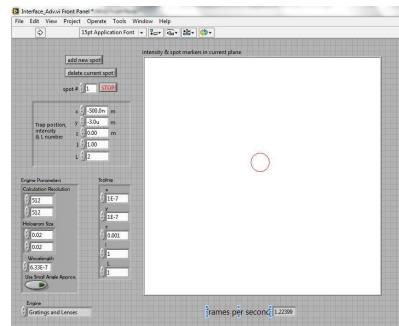

FIG. 6: This interface was used to control the locations and the number of optical traps produced by the computed hologram. When running the program, moving a spot on the screen will change the hologram in real time.
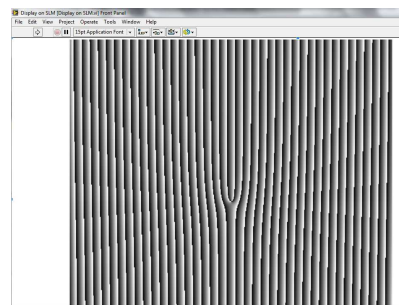

FIG. 7: Image produce by the Interface Adv.vi. By changing the location and the azimuthal index of the optical traps (spots) change the design and orientation of the hologram.

University optics web page [9]. On their website, there are two versions of the LabVIEW code available to download, both capable of producing the necessary holograms. The newest program was named the Red Tweezers and used for advanced hologram and filming of optical traps. The original version was named the Blue Tweezers and was simpler to use for this experiment. Initiating the program generated two interfaces corresponding to the Interface Adv.vi and The Display on SLM.vi . The Interface Adv.vi is seen in Fig. 6 and has several components that allow for the computed holograms to be altered. The vi had the ability to add optical traps to any location on the screen by mouse or typing in the locations manually, increase the intensity of those traps and change the azimuthal index number to any degree for each trap. The vi also had the ability to adjust the holograms for different wavelengths with 633 nm set as default. The engine could be changed into several different algorithms that could produce different types of holograms. In this experiment, the engine used was the grating and lenses algorithm in order to have holograms that would produce the LG modes. When the program was activated, the hologram was then displayed on the Display on SLM.vi as seen in Fig. 7. One issue with the program was that it defaulted to putting the hologram onto the primary screen (the computer) rather than the
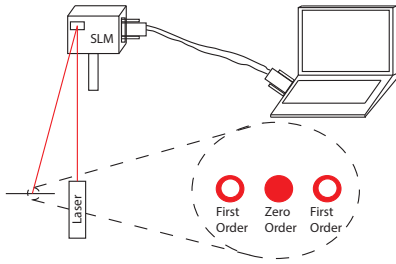
FIG. 8: The SLM was connected to the computer in order to produce the hologram. A laser was then directed at the hologram where the defect is located. The far-field image would result in multiple orders of reflection, where the first order reflection would be the LG modes.
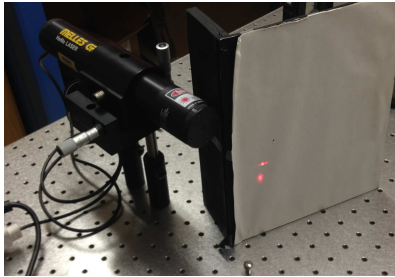

FIG. 9: The image is produced on the paper next to the laser. The long distance allows for the diffraction patterns to converge into a image.
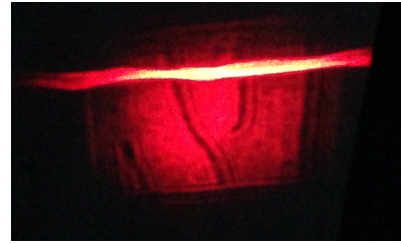

FIG. 10: Schematic showing the result if the laser beam's radius was too large for the SLM. This image was enlarged using a 300mm lens.
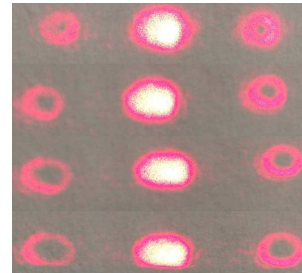

FIG. 11: Compilation of images of various LG modes that were the result of back reflection off the SLM's screen using the laser. Starting from the top, the azimuthal index was equal to 1 and progressed down to $l = 5$. As the azimuthal index increased, the donut shapes became more distinct and the waist of the ring became smaller.

SLM (the second monitor) when running. Thus real time alterations to the hologram was not possible. However, it was possible to generate the desired hologram by stopping the program and then going to the display vi and converting the image to be sized for the second monitor. This allowed the image then be dragged into the second monitor screen and expanded to fix the size of the screen on the SLM.

The laser used in the experiment was a Melles Griot HeNe laser operating at 633 nm. This laser produced a beam that was collimated, which means as the laser continues through space, the beam's radius does not increase or decrease in size. The beam was directed to the SLM screen which had the computed hologram as seen in Fig. 8. The SLM was mounted on a three-dimensional translation stage in order to have precise and easier control of the location of the SLM screen. If the laser strikes where the defect was in the hologram and the beam radius was the correct size, then the backwards reflection would produce the LG modes as seen in Fig. 9. A long distance from the SLM was needed for the images to focus to the far-field image and show the LG modes.

IV. RESULTS AND ANALYSIS

In order to produce the LG modes, the laser beam had to be the right size and hit the hologram's defect just right. If the laser beam's radius was too big for the hologram, the image returned off the SLM would just be an expanded image of the hologram as seen in Fig. 10. If the laser beam's radius was the right size and directing at the hologram where the defect was located would result in images as seen in Fig. 11. These are LG modes of different azimuthal index values and will produce OAM. The middle red dot in Fig. 11 represents the zero order which is equivalent to a mirror. The donut shapes on the left and right of the middle red dot are the first order and represent the light after it passes through the defect in the hologram. The top row displays a LG mode of an azimuthal index of $l = 1$, which means that OAM for that particular LG mode would be $\hbar$ per photon. As the azimuthal index increases (which was done by increasing the L value in the LabVIEW program), the rings width begin to decrease. Figure 12 show a LG mode when the azimuthal index is 20. The different orders of light can be spread out by increasing the number of lines in the hologram, allowing them to be more distinguishable.

V. TROUBLESHOOTING

In order to produce and observe the LG modes, the setup and the hologram had to be positioned correctly. The hologram had to have a similar structure as the hologram seen in Fig. 2. If the hologram was rotated, then
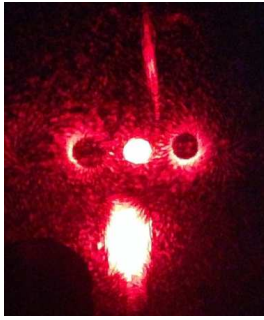
FIG. 12: Image of a LG mode with $l = 20$. With the azimuthal index so large, the rings are barely there. Underneath the image was back scattered light.

it became very hard to distinguish the different modes of light. Also, I was unable to do real-time alterations to the hologram if I wanted to project the hologram onto the SLM. The hologram had to first be computed and then dragged on the SLM screen in order to produce the LG modes. At first, a beam expander was used to increase the radius of the laser beam in hopes of seeing the LG modes. However, this did not help in producing the LG modes but rather produced a back reflected image of the hologram as seen in Fig. 10. The setup that finally worked was to have the back scattering image a long distance from the SLM. The back reflection off the SLM's screen was then focused on piece of paper next to the laser to produce the LG modes.

VI. CONCLUSION

A SLM is a very useful tool when it comes to optics. Coupled with a program to generate any type of hologram, SLMs could be crucial for producing different modes of light. However, generating this type of light is not an easy task. It requires the laser beam radius be the right size such that when directed at the hologram's defect, it will be reflected and produce the LG modes. The hologram itself must also be oriented in the correct way and the light must pass through the defect in the hologram to produce the LG modes. When the the setup is correct, the light reflected back is the LG mode. Of the backscattered light, the center red dot is a reflection off the SLM screen and is known as the zero order and acts as a mirror. The two red dots to the left and the right of the middle red dot are the first order reflections and are the LG modes. In fact all the orders after that are also LG modes. I produced LG modes of light with azimuthal indexes ranging from 1-20, with each increasing their OAM by $l\hbar$ per photon.

Future goals are to use this LG mode of light to optically trap and rotate a particle and measure the value of the OAM. While the I was using the grating and lenses engine to generate my hologram, other engines that are implemented in the program can create much more complicated holograms. I hope to further investigate these engines and see what other types of modes I can produce. Also, using the results from [6], I hope to further optimize this SLM to increase the diffraction efficiency.

VII. ACKNOWLEDGMENTS

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