Abstract

An orbital angular momentum (OAM) sorter concept was designed for high-speed data transfer. The OAM of a light beam known as an optical vortex can exist in one of an infinite number of states and may be used to carry information. The augmented alphabet of states carries the potential to increase data transfer speeds over conventional binary (0 and 1) methods. A vortex generator, or OAM encoder, was constructed form a slit cover slip functioning as an adjustable spiral phase plate, and a vortex analyzer, or OAM measurer, was created using a transparent print of a computer-generated hologram. The two components were then incorporated in an OAM sorter concept that employs a novel combinatoric method for sorting data. The vortex generator and analyzer created were inexpensive simplifications of previous devices and have the potential to increase the alphabet of transmission states several thousand times over binary methods if implemented in the OAM sorter concept.

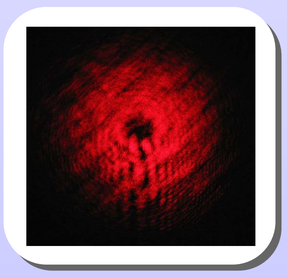
Purpose

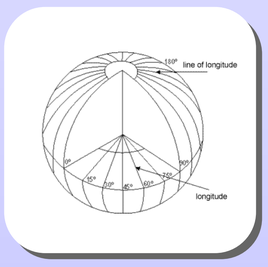
The objective of this research was to develop practical and inexpensive optical devices that may be used to modify and detect the orbital angular momentum (OAM) state of a light beam.

Introduction

There has always been a motivation to increase the pace at which information is transmitted, and light has proved an ideal medium for high-speed data transfer, most notably through fiber optic networks. Recent advances in free-space communication systems, however, have revived interest in optical links outside the sphere of fiber optics. Free-space systems function without wave guides, making them better suited for temporary connections and areas where deploying a fiber optic cable is logistically unfeasible. These links rapidly modulate the intensity, frequency, or polarization of light between two states, representing the 0s and 1s of binary data transfer. Clearly, an augmented alphabet of more than two states would permit much faster transmissions.

Recently, it has been shown that laser light beams can be given a property, orbital angular momentum (OAM), that offers this possibility. In contrast to polarization encoding, the number of possible OAM states of a light beam is limited only by practical considerations. Thus, OAM-encoding can conceivably be used to substantially increase the rate of data transfer over conventional binary methods. Light beams that carry OAM are called optical vortices. They are characterized by a spiral-shaped phase distribution that creates a region of zero field amplitude in the center of the beam. The rate at which the phase advances around the circumference of the beam is proportional to the OAM of its photons.

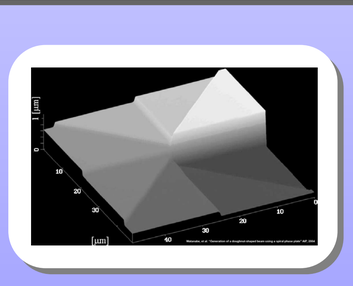




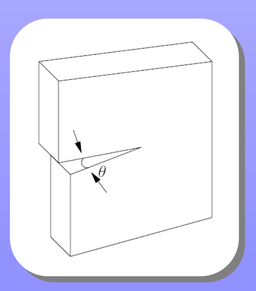
$$U_l^p(r,\phi,z) = \exp\left[-\frac{ikr^2}{2R} - \frac{r^2}{w^2} - i(2p+l+1)\psi\right]\exp[-il\phi](-1)^p\left(\frac{r^2}{w^2}\right)^{\frac{l}{2}} L_p^l\left(\frac{2r^2}{w^2}\right)$$

The research described in this report has three principal components related to the overall goal of designing and demonstrating a practical and effective OAM transmission scheme.

- In the first and most detailed study, an adjustable spiral phase plate was investigated and mathematically modeled to better understand its vortex generation capability.
- Second, a composite grid computer-generated hologram (CGH) was developed to analyze the vortices, or measure their OAM.
- Finally, a conceptual design of an OAM sorter based on the two components was proposed and analyzed mathematically.



$$\Lambda = \int n(s)ds$$

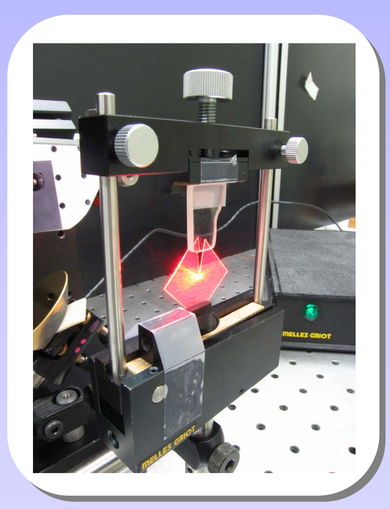


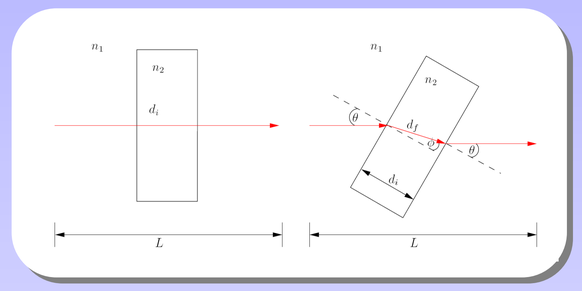
The Development of an Orbital Angular Momentum Sorter for High-Speed Data Transfer

• Amol Jain • United States •

Methodology

Spiral Phase Plate



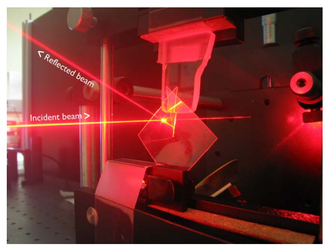


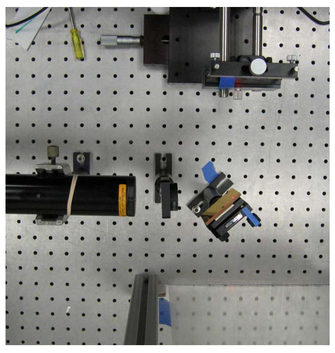
- A standard "unbreakable" cover slip (22 mm square, 0.25 mm thick) was slit radially from center to a corner and placed in a modified lens holder to create the spiral phase plate device.
- The CJ Interferometer was developed to test the phase plate.
- An experiment was conducted to determine the relationship between the cover slip's tilt angle and the incident light's resultant phase shift.

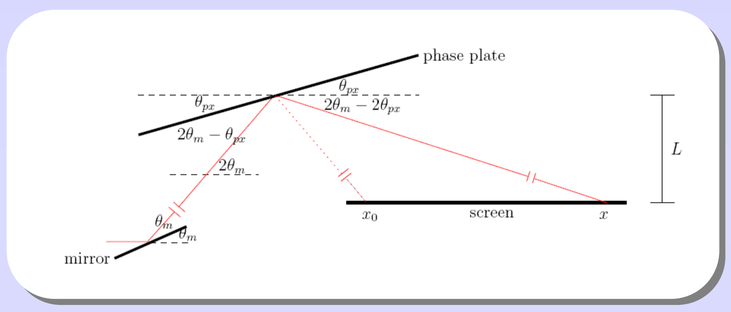
$$\Delta\Lambda = d_i\left[n_1\left(1-\frac{\cos(\theta-\phi)}{\cos(\phi)}\right)+n_2\left(\frac{1}{\cos(\phi)}-1\right)\right]$$

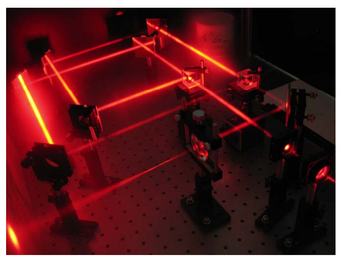
$$\sin\phi = \frac{n_1\sin\theta}{n_2}$$

- A surface scan of the cover slip was performed at 0.508 mm increments over a 10.16 mm by 10.16 mm area to determine the tilt angle at various points.





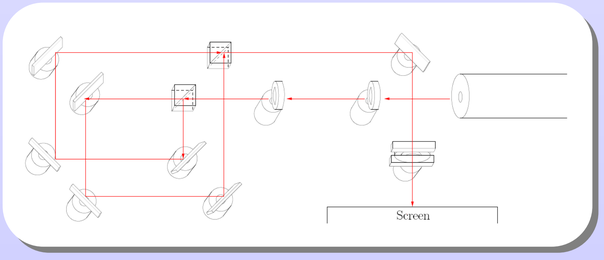




$$\theta_{px} = \theta_m - \frac{1}{2}\tan^{-1}\left(\frac{L}{x+x_0}\right)$$

$$\theta_{py} = \tan^{-1}\left(\frac{y}{L\sqrt{1+\cot^2(2(\theta_m-\theta_{px}))}}\right)$$

$$\cos(\theta_t) = \cos(\theta_x)\cos(\theta_y)$$



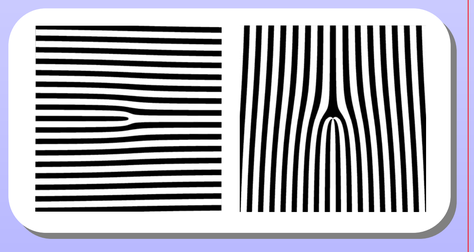
Computer-Generated Holograms

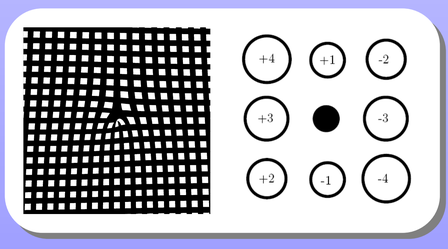
- A hologram is essentially an interference pattern between a plane reference wave and another wave. It can reconstruct its constituents.
- The CGH transmittance function was calculated for 1800x1800 pts in a 16x16 unit square centered on the origin then exported as an image in Matlab.
- The image size was reduced to 120x120 pixels and then printed at 10% its size onto a common transparency by a 600 dpi laser printer.

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

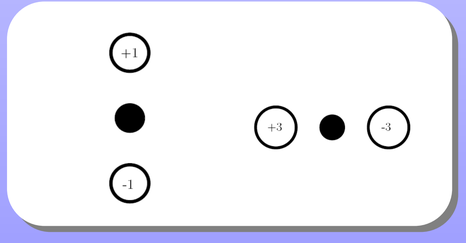
$$u = \exp(-ik_x x - ik_z z)$$

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

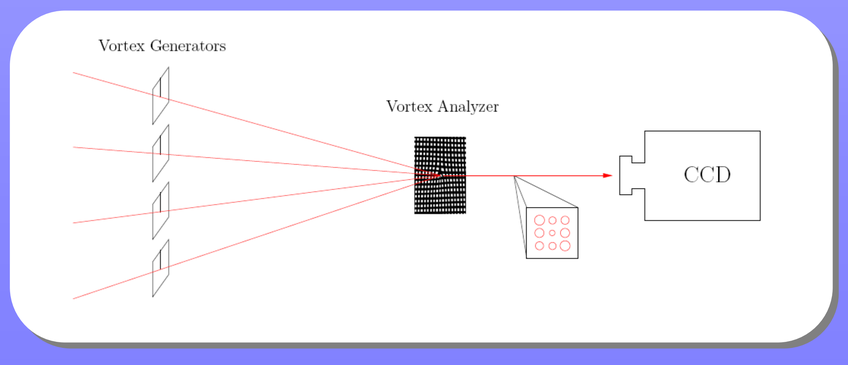




$$T(r,\theta) = T_0\exp\left[i\alpha\cos\left(l\theta - \frac{2\pi}{\Lambda}r\cos\theta\right)\right]$$

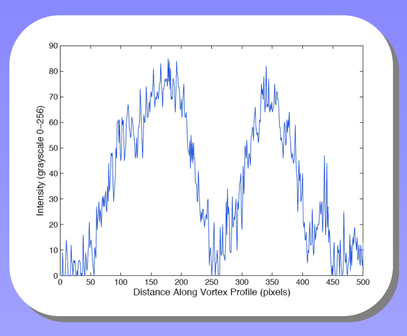


OAM Sorter

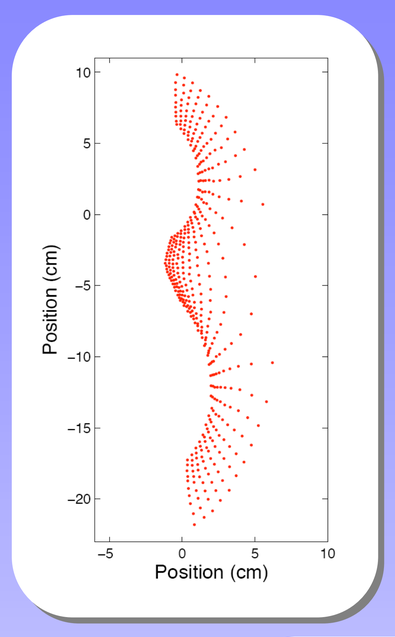


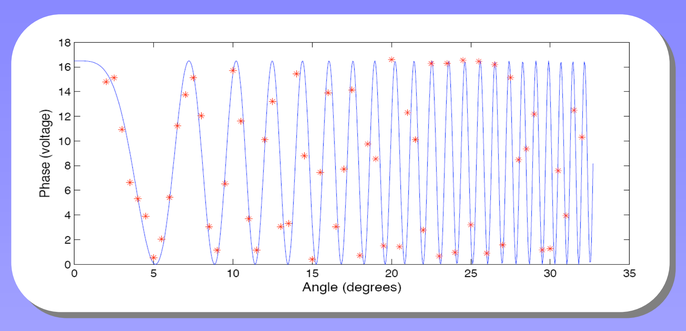
- A conceptual method for sorting vortex beams by their orbital angular momentum was developed with two components, spiral phase plates and composite grid CGHs, and a novel combinatoric approach to increasing the alphabet of states available for data transmission.
- The theoretical vortex analyzer (CGH) can test for up to 8 OAM states simultaneously. The results are picked up by the CCD camera.
- The vortex generators (spiral phase plates) operate independently and encode vortices of different topological charge.

Results



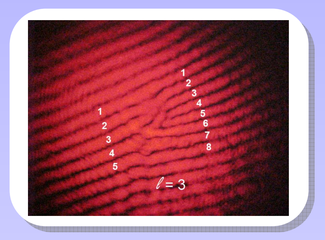
- Intensity distributions of beams leaving the phase plate demonstrated vortex-character.
- The data from the surface scan was translated into the tilt of the phase plate at various points.
- The derived function relating tilt angle to phase was experimentally confirmed.

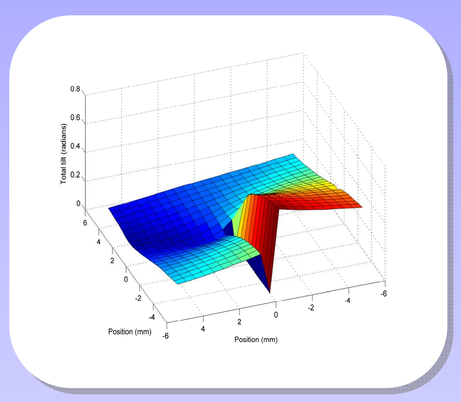


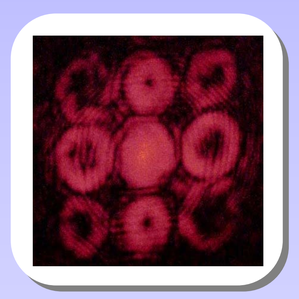


$$p(\theta) = \cos\left(2\pi\frac{d_i}{\lambda}\left[n_1\left(1-\frac{\cos(\theta-\phi)}{\cos(\phi)}\right)+n_2\left(\frac{1}{\cos(\phi)}-1\right)\right]\right)$$

- Forked patterns were observed in the interferometer with the phase plate.



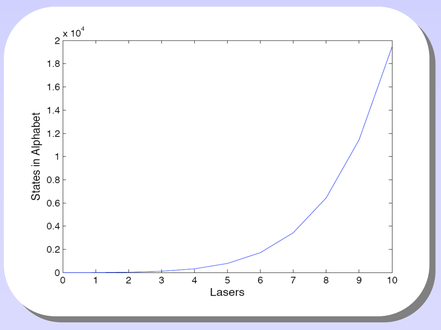




- The composite grid CGH successfully generated optical vortices when a plane wave was shined through.
- The phase plate's spiral phase pattern demonstrated vortex characteristics.

$$S = \frac{(t+g-1)!}{g!(t-1)!}$$

- A combination-with-replacement function was found to model the OAM sorter.
- The alphabet of available states grew at an extremely rapid state as more lasers were added to the OAM sorter scheme.



g	S
1	8
2	36
3	120
4	330
5	792
6	1716
7	3432
8	6435
9	11440
10	19448

Discussion

- The spiral phase plate successfully created optical vortices (up to charge 7) as evidenced by the two-peaked intensity distribution, the forked patterns resulting from experimentally interfering the spiral phase plate's beam with a plane wave, and the spiral phase variation on the cover slip.
- Imperfections in the phase structure may have been due to irregular bending or stress on the cover slip.
- The CGHs were demonstrated to be effective in recreating vortices from a reference plane wave, but as of the present, using them to measure the OAM of incident vortices has not yielded conclusive results.
- The spiral phase plate was found to be an extremely inexpensive alternative to traditional static phase plates.
- The possibility of creating CGHs from readily available materials was demonstrated successfully and allows for prompt testing of various CGH designs in contrast to the more common, slower process of photo-reducing the patterns.
- The OAM sorter, though not truly practical with this exact equipment, presented how optical vortices can be used to advance data transfer speeds.

Conclusion

The adjustable spiral phase plate constructed from a plastic microscope cover slip was demonstrated to be an effective means of producing optical vortices, which can be used to encode information into light beams. The phase plates produced are inexpensive and 100\% efficient, making them suitable for applications that require high-intensity beams such as optical tweezers. The phase distribution of the vortices produced was successfully mapped by performing a surface scan of the phase plate, and intensity profile measurements confirmed vortex characteristics. A simplified method for analyzing optical vortices using computer-generated holograms was also investigated and partially implemented in the form of a composite vortex grid.

These two components were then integrated in a conceptual OAM sorter that employs a novel combinatoric transmission method to increase the alphabet of states used for data transmission thousands of times over traditional binary methods. Although the sorter requires improvements before becoming practical for actual usage, it demonstrates the promise of using the orbital angular momentum of photons for high-speed data transfer.

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