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|  | **Universidade de Aveiro**  **Ano 2024** |  | |
| MOHAMED  HADDADI | TÍTULO (MÁXIMO 130 CARACTERES) | | |
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|  | Projeto final apresentado à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Licenciatura em física, realizado sob a orientação científica do Doutor Gil Fernandes, Professor (categoria do orientador) do Departamento de (designação do departamento) da Universidade de Aveiro | |

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C 1

**Introduction**

Communication plays a crucial role in the current and future scenario, driving globalization, innovation and collaboration in various sectors, while also facilitating the dissemination of knowledge and education around the world. In the business world, effective communication is the backbone of successful operations, allowing coordination between globally distributed teams and enabling rapid adaptation to market changes. Furthermore, in the educational sphere, communication plays a vital role in delivering educational content to a wide audience, allowing students and teachers to interact efficiently, regardless of physical distance.

In this context, advanced technologies such as fiber optics play a crucial role, offering high bandwidth and low latency to support the growing demand for fast and reliable communication. However, optical fibers face significant challenges, such as chromatic dispersion, which can distort the transmitted signals, and attenuation, which limits the transmission distance. In addition, the non-linearity of optical fibers can introduce distortions in signals at high transmission powers.

To overcome the inherent limitations of optical fibers and advance the capacity and efficiency of communication networks, innovative solutions are being developed that address specific challenges.

Structured light

Structured light involves the deliberate manipulation of light across its various properties. This manipulation can include shaping light in terms of its timing and frequency to generate precise pulses, or more commonly, controlling its spatial characteristics like polarization, intensity, and phase.

The use of structured light is one such solution, where the spatial pattern of light is manipulated to optimize data transmission, and this can involve various techniques such as the following:

Bessel beams, which are being explored because of their ability to maintain their shape during propagation, which minimizes dispersion and preserves signal integrity, thus enabling more reliable communication over long distances. This unique property of Bessel beams makes them particularly valuable in applications that require high-quality transmission in challenging conditions.

In addition, Hermite-Gauss and Laguerre-Gauss beams are being developed to mitigate chromatic dispersion, a phenomenon that causes distortion in transmitted signals at different wavelengths. These beams have been designed with specific intensity distributions that minimize chromatic dispersion, thus improving the efficiency of optical fiber communication and allowing the use of a wider range of wavelengths.

As we know, an electromagnetic wave is capable of carry both energy and momentum, and momentum comprises linear momentum **P** and angular momentum **L**. Addictively, angular momentum has one more component linked to polarization, spin angular momentum (SAM), and another one, orbital angular momentum (OAM), associated with spatial distribution.

Orbital Angular Momentum Multiplexing (OAM) technology, allows multiple channels of information to be transmitted simultaneously on a single optical fiber, significantly increasing data transmission capacity. Light is encoded with different values of orbital angular momentum, that can take on an infinite number of values. Each value of orbital angular momentum can be used to encode a separate channel of information, thus allowing the simultaneous transmission of multiple channels of information on a single optical fiber.

And this results in a significant increase in available bandwidth, enabling faster and more efficient communication.

However, despite its many advantages, OAM technology still faces several technical challenges that need to be overcome. For example, generating and detecting light beams with orbital angular momentum requires complex and precise optical devices. In addition, light beams with orbital angular momentum can be affected by atmospheric turbulence, which can degrade transmission quality.

The aim of this study is to delve into the realm of structured light by generating Hermite-Gaussian, Laguerre-Gaussian, and Bessel beams, alongside beams carrying Orbital Angular Momentum (OAM), employing Spatial Light Modulators (SLMs). Subsequently, we will conduct a comparative analysis between the experimentally generated beams and their theoretical counterparts. Additionally, if necessary, we will employ refinement techniques to enhance the purity of the generated beams.

This work comprises a total of six chapters, commencing with this introduction leading into the subsequent chapters:

Theoretical Foundation: This chapter will delve into the theoretical underpinnings of structured light and its significance in communication technologies. It will explore concepts such as Bessel beams, Hermite-Gauss, and Laguerre-Gauss beams, as well as the principles of orbital angular momentum (OAM).

Structured Light Generation Techniques: This chapter will provide an in-depth examination of various techniques used to generate structured light, including Bessel beams, Hermite-Gauss and Laguerre-Gauss beams, and beams carrying OAM. It will discuss the principles behind each technique and their applications in communication systems.

Setup and GUI: This chapter will describe the experimental setup used in the study, including the equipment and software employed for generating and analyzing structured light. It will also detail the graphical user interface (GUI) developed for controlling the experimental setup, generating and collecting data.

Results: This chapter will present the results of the experimental study, including the generation and characterization of structured light beams. It will analyze the purity and efficiency of the generated beams and compare them to theoretical expectations.

Conclusion: This chapter will summarize the findings of the study and discuss their implications for communication technologies. It will also highlight areas for future research and development in the field of structured light generation and its applications in communication systems.

C 2

**Theoretical foundation:**

2.1 Paraxial Helmoltz equation:

Maxwell's equations are fundamental equations in classical electromagnetism. They describe how electric and magnetic fields interact and propagate in space. The four Maxwell's equations are:

Gauss's Law for Electricity:

|  |  |  |
| --- | --- | --- |
|  |  | (2.1) |

Gauss's Law for Magnetism:

|  |  |  |
| --- | --- | --- |
|  |  | (2.2) |

Faraday's Law of Electromagnetic Induction:

|  |  |  |
| --- | --- | --- |
|  |  | (2.3) |

Ampère's Law with Maxwell's Addition:

|  |  |  |
| --- | --- | --- |
|  |  | (2.4) |

Where:

- is the electric field,

- is the magnetic field,

- is the vacuum permittivity (electric constant),

- is the vacuum permeability (magnetic constant),

And , is the speed of light in vacuum.

These equations govern the behavior of electromagnetic fields in vacuum.

Helmoltz equation:

If we apply the rotational operator to equation 2.1, we get

|  |  |  |
| --- | --- | --- |
|  |  | (2.5) |

And by replacing the second term of the above equation with equation 2.2 we get

|  |  |  |
| --- | --- | --- |
|  |  | (2.6) |

Substituting the identity

|  |  |  |
| --- | --- | --- |
|  |  | (2.7) |

In the equation 2.6, and since we know that is zero (from equation 2.3) we can get the equation of propagation of the electric field:

|  |  |  |
| --- | --- | --- |
|  |  | (2.8) |

The above equation in general can be known as the equation for a quantity that propagates like a wave.

To study monochromatic waves, we know that the wave phasor only depends on the position and provides a sufficient description of the disturbance.

The variable separation process can be used in equation 2.8 to obtain the time independent equation of propagation, also known as the Helmholtz equation.

(2.9)

|  |  |  |
| --- | --- | --- |
|  |  | (2.9) |

eqnm

Where is the wave number.

In that derivation we are assuming a medium with known sources or losses, and since we are studying beams which propagate in air and are monochromatic, these assumptions are still valid.

Paraxial Helmholtz equation:

A paraxial wave is essentially a type of wave where we can simplify the governing equation due to certain assumptions. We can Imagine a wave traveling straight ahead in the z-direction, with its intensity fluctuating slowly compared to its overall strength. In simpler terms, it's like a gentle wave that doesn't change too rapidly over short distances.

So, when we're dealing with such waves, we can approximate the equation that describes them. Picture a flat, single-colored wave with a certain height (amplitude) and a specific length (wavelength) λ. Now, if we consider that the change is smaller than U itself, in a distance , it may be asserted that:

(2.10)

|  |  |  |
| --- | --- | --- |
|  |  | (2.10) |

And we know that , so

(2.11)

|  |  |  |
| --- | --- | --- |
|  | . | (2.11) |

To complete that approximation, we need to assume that the derivative of U must be itself a slow varying function of z such that:

(2.12)

|  |  |  |
| --- | --- | --- |
|  | , | (2.12) |

So, consequently we have that:

|  |  |  |
| --- | --- | --- |
|  |  | (2.13) |

When we plug the expression for the paraxial wave envelope into equation 2.9 and disregard the smaller terms, we end up with what’s called the paraxial Helmholtz equation.

|  |  |  |
| --- | --- | --- |
|  |  | (2.14) |

Where is the transverse Laplacian operator.

In simpler terms, it’s like swapping in our simplified wave description a bigger equation and ignoring the less significant bits, what we are left with is a more focused equation that describes the behavior of paraxial eaves specifically.

changing the boundary conditions, we arrived at several solutions for this equation, we will focus on the most notable ones in this work.

Beams

Gaussian beams

The gaussian beam can be interpreted as a shifted version of the paraboloidal witch is given by:

(2.15)

|  |  |  |
| --- | --- | --- |
|  |  | (2.15) |

We can confirm that the above equation satisfies both equation 2.9 and 2.14 due to its small variation across distance comparable to its wavelength.

When we replace z in equation 2.15 by , where represents a simple shift in position, and represent the same wave but centered in .

It remains a solution of the Helmholtz equation even if ξ is complex. If that is the case, the solution acquires very different properties and in the particular case that ξ is a pure imaginary, we get the complex envelope of the Gaussian beam,

(2.16)

|  |  |  |
| --- | --- | --- |
|  |  | (2.16) |

Where is the Rayleigh range and is the cartesian distance.

(2.17)

|  |  |  |
| --- | --- | --- |
|  |  | (2.17) |

and as

|  |  |  |
| --- | --- | --- |
|  |  | (2.18) |

|  |  |  |
| --- | --- | --- |
|  |  | (2.19) |

Combining equations 2.18, 2.19 and equation 2.16, we can write equation 2.16 as

(2.20)

|  |  |  |
| --- | --- | --- |
|  |  | (2.20) |

And can be simplified to

|  |  |  |
| --- | --- | --- |
|  |  | (2.21) |

Where,

|  |  |  |
| --- | --- | --- |
|  |  | (2.22) |

|  |  |  |
| --- | --- | --- |
|  |  | (2.23) |

Hermite-Gaussian beams:

As we know, the Gaussian beam is not the only beam-like solution of the paraxial Helmholtz equation (2.14),

There are solutions that have non-Gaussian intensity distributions but share the same wave fronts as gaussian beams, this means they have the same curvature of wavefronts as gaussian beams. One example of non-gaussian beams with gaussian wavefronts are Hermite-gaussian beams. They are solutions to the paraxial Helmholtz

equation in the cartesian coordinate system. These beams have intensity distributions that exhibit a petaloid structure, meaning they have lobes or petals in their intensity profile.

|  |  |  |
| --- | --- | --- |
|  |  | (2.22) |

Where,

|  |  |  |
| --- | --- | --- |
|  |  | (2.24) |

Laguerre-Gaussian beams:

In the other hand, there is another famous solution to the paraxial helm eq, an approximate solution in the cylindrical coordinate system. They have different intensity distribution compared to Hermite-Gaussian beams, with concentric ring instead of petals.

|  |  |  |
| --- | --- | --- |
|  |  | (2.23) |

Here, ​ represents generalized Laguerre polynomials, where the integers l = 0,1,2,.. and m = 0,1,2,… are azimuthal and radial indices, respectively. The functions 𝑊(𝑧), 𝑅(𝑧), 𝜁(𝑧), and 𝑊0​ are defined by equations (2.19), (2.20) and (2.23). The integers 𝑙=0,1,2,...l=0,1,2,... and 𝑚=0,1,2,...m=0,1,2,... represent the azimuthal and radial indices, respectively. The fundamental Laguerre-Gaussian beam ​, akin to the lowest-order Hermite-Gaussian beam ​, corresponds to the simple Gaussian beam.

Bessel beams:

When searching for beam-like waves, we often seek waves with planar wavefronts but nonuniform intensity distributions in the transverse plane. This means that the phase of the wave remains constant along a plane (the wavefront), but the intensity varies across the cross-section of the beam.

One way to achieve this is by considering a wave with a complex amplitude 𝑈(𝑟), where 𝑟 represents the position vector in the transverse plane. In other words, the wave is described by a complex-valued function that varies across the transverse plane.

|  |  |  |
| --- | --- | --- |
|  |  | (2.25) |

In order fot the wave described by the complex amplitude 2.22 satisfy the Helmholtz equation 2.9, the quantity A(x,y) must satisfy the condition:

|  |  |  |
| --- | --- | --- |
|  |  | (2.26) |

Where and is the transverse Laplacian operator.

The quation 2.23 is known as the two-dimensional Helmholtz equation, may be solver by employing the method of separation of variables using polar coordinates:

|  |  |  |
| --- | --- | --- |
|  |  | (2.27) |

In simpler terms, the conditions described ensure that the wave has planar wavefronts, meaning that the wavefronts (the surfaces where the phase of the wave is constant) are all flat and parallel to the z-axis. This implies that the rays of the wave (the lines perpendicular to the wavefronts that indicate the direction of energy propagation) are also parallel to the z-axis.

Additionally, the intensity distribution of the wave is circularly symmetric, meaning that it looks the same when viewed from any direction around the z-axis and varies with .Consequently, the intensity distribution does not change as the wave propagates along the z-axis, meaning there is no spread of the optical power in the z-direction.

This particular type of wave, with planar wavefronts and circularly symmetric intensity distribution that remains constant along the z-axis, is known as a Bessel beam.

Orbital Angular Momentum

Orbital Angular Momentum (OAM) is a property of light beams that arise from their spatial structure rather than their polarization. Unlike the familiar Spin Angular Momentum (SAM), which is associated with the polarization of light (e.g., circular polarization), OAM is related to the phase distribution of the light beam.

The concept of OAM in light beams was recognized by Allen et al. in 1992. They found that light beams with a specific phase dependence, such as , carry an OAM that can be significantly greater than the SAM.

Essentially, OAM refers to the rotation or twisting of the wavefront of a light beam around its axis of propagation.

In classical electrodynamics, the electric field **E** and magnetic field **B** of a light wave are described by Maxwell's equations. For simplicity, let's consider a monochromatic electromagnetic wave propagating in the z-direction:

|  |  |  |
| --- | --- | --- |
|  |  | (2.25) |

|  |  |  |
| --- | --- | --- |
|  |  | (2.26) |

The phase term represents the spatial and temporal dependence of the wave. The phase factor 𝑘⋅𝑧 contributes to the spatial phase variation along the propagation direction.

When discussing OAM, we introduce a phase term in addition to the plane wave term. Here, 𝜙 represents the azimuthal angle around the propagation axis, and 𝑙 is an integer that quantifies the OAM, also known as the "topological charge".

So, the electric and magnetic fields of a light beam with OAM can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (2.27) |

|  |  |  |
| --- | --- | --- |
|  |  | (2.28) |

The presence of the term introduces a spatial phase variation around the propagation axis, giving rise to the twisted wavefront characteristic of OAM-carrying beams.

Perhaps the most active, and arguably most contentious, of OAM sub-field of recent years has been the application of OAM to optical communication. The key motivation being that whereas the spin angular momentum of light has only two orthogonal states, the OAM has potentially an unlimited number of states.

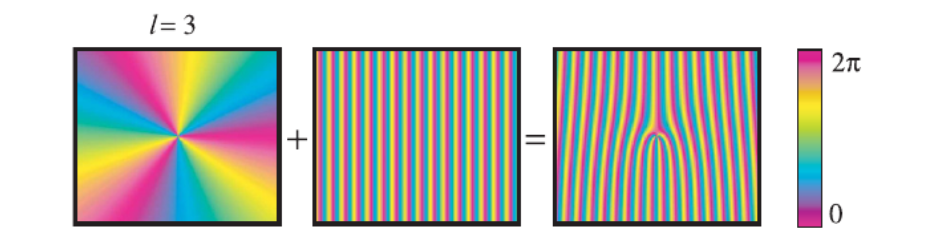
forked diffraction gratings:  


Figure 1 - A combination of the phase distribution of the desired optical component (left)plus a linear phase ramp (middle) creates a forked diffraction grating (right), which can produce a helically phased beam. In this case l= 3.

[(PDF) Orbital angular momentum: Origins, behavior and applications (researchgate.net)](https://www.researchgate.net/publication/247164595_Orbital_angular_momentum_Origins_behavior_and_applications)

A combination of the phase distribution of the desired optical component (left)

plus a linear phase ramp (middle) creates a forked diffraction grating (right),

which can produce a helically phased beam. In this case ` = 3.

A helical phase profile, denoted by exp(iθ), is capable of transforming a Gaussian laser beam into a helical mode, where the wavefronts resemble a corkscrew with θ-fold symmetry. This effect arises due to the introduction of Orbital Angular Momentum (OAM) into the beam, as discussed in the preceding explanation regarding how a beam can carry OAM.

In practical implementations, achieving this transformation involves combining the phase distribution of the desired optical component with a linear phase ramp. The resultant sum is expressed modulo 2π, as illustrated in the subsequent discussion. This combined phase profile effectively acts as a diffraction grating, generating the desired beam in the first diffraction order.

The complex field resulting from this combination can be represented as:

|  |  |  |
| --- | --- | --- |
|  |  | (2.) |

Where, and are the number of spacings in x and y respectively.

The components comprising this phase profile are akin to holograms of the desired optical element and are commonly referred to as "computer-generated holograms." Specifically, in the context of producing helical beams, these holograms often take the form of "forked diffraction gratings" as explored in the literature.

[OptExpress2017Padgett.pdf](file:///C:\Users\moham\AppData\Local\Temp\MicrosoftEdgeDownloads\9d351d52-a71e-4b7b-8521-64e3f41458c1\OptExpress2017Padgett.pdf)

Beam propagation (simulation?) :

Fresnel diffraction integral:

The Fresnel diffraction integral allows for the calculation of the intensity distribution of diffracted light at specific observation points after passing through apertures or circumventing obstacles. This integral take into account both amplitude and phase modulations in the diffracted wave, described as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (2.) |

Fraunhofer Diffraction:

Fraunhofer diffraction is a valid approximation for situations where the distance between the light source and the observation plane is significantly larger than the dimensions of the diffracting structures. In this approximation, the quadratic phase term in the Fresnel integral is removed, simplifying it to a more tractable form:

|  |  |  |
| --- | --- | --- |
|  |  | (2.) |

This allows for the direct evaluation of the intensity distribution at the observation plane through a Fourier transform.

According to Goodman, “significantly larger” is defined by the inequality:

|  |  |  |
| --- | --- | --- |
|  |  | (2.) |

Convolution:

Convolution is a mathematical operation that describes how tow functions combine to produce a third function. In optics, describes how light is diffracted as it passes through apertures or circumvents obstacles. In the context of beam propagation simulation, convolution is often used to calculate the intensity distribution of light at the observation plane, taking diffraction into account.

|  |  |  |
| --- | --- | --- |
|  |  | (2.) |

The convolution integral is equivalent to multiplication in the frequency domain. Then, by inverse Fourier transfomrint both sides:

|  |  |  |
| --- | --- | --- |
|  |  | (2.) |

C3

structured light manipulation overview

Optical elements

Optical Vortices

An optical vortex is an optical field that exhibits a line of zero optical intensity, such as the line along the axis of a Laguerre– Gaussian beam with l ≠ 0. It is also called a screw dislocation since the phase of the field is twisted like a corkscrew about the axis of travel. An optical vortex in a plane is a point at which the optical field vanishes; it is also called a phase singularity. The strength of a vortex is indicated by its topological charge, which is determined by the number of full twists that the phase undergoes in a distance of one wavelength. For the Laguerre– Gaussian beam, the topological charge is the azimuthal index l, which is indicated by the number of lines of zero intensity that appear in the standing wave generated by the combination of two beams of the same order but opposite handedness. This number also determines the orbital angular momentum of the associated photon.

Axicons:

Axicons are optical components characterized by their conical shape. They have a unique property of focusing incident light into a ring-shaped intensity distribution rather than a conventional focal spot. This effect arises due to the gradual change in the phase of light as it passes through the axicon's surface.

As light passes through an axicon, its phase undergoes a continuous change, resulting in the formation of an annular intensity pattern in the focal plane.

Diagram of a diagram of a triangle with arrows and a red line

Description automatically generated

Figure 2- Schematic diagram for zero-order Bessel generation by Axicon, where γ is the base angle of the axicon

Cylindrical lenses:

Cylindrical lenses are optical components with a curved surface that focuses light asymmetrically along one axis, producing astigmatic beams. This asymmetry introduces a phase gradient across the beam profile, enabling the generation of structured light, including beams carrying Orbital Angular Momentum. The phase profile imparted by a cylindrical lens can be approximated as: ​

Diagram of a diagram of a circular object

Description automatically generated

Figure 3 – The cylindrical lens mode converter for the conversion of a Hermite-Gaussian x=1, y = 0 mode into the corresponding Laguerre-Gaussian mode with l=1 and p = 0. The lenses of focal length f are separated by where Rayleigh eange of the input beam is

Spical phase Plates:

Spiral phase plates (SPPs) are diffractive optical elements designed to impart a helical phase structure onto an incident beam. This phase structure results in the formation of optical vortices, which carry Orbital Angular Momentum (OAM). The phase profile of an SPP is given by:,

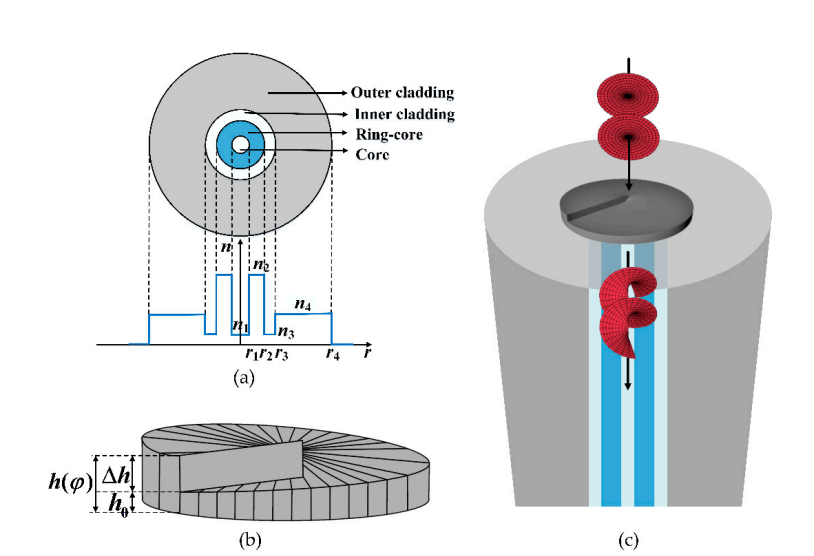


Figure 4 (a) Cross-section of the designed spiral phase plate in schematic form; (b) Schematic of the construction of SPP; (c) Schematic of the OAM beam generated by the SPP

Holographic Gratings:

Holographic gratings are optical elements that use interference patterns to diffract incident light into specific directions, based on the spatial variation of the refractive index. By engineering the interference pattern, holographic gratings can generate structured light patterns, including beams with specific phase profiles and intensity distributions.

A diagram of a beam and a beam

Description automatically generated

Optical fibers:

Long-period-grating (LPG)….  
chiral-long-period-fiber-grating (CLPFG)…

Photonic Crystal Fiber

Photonic crystal fibers (PCFs) are optical fibers with a microstructured design, typically consisting of a periodic arrangement of air holes or voids running along the length of the fiber. This unique structure allows for precise control over the behavior of light transmitted through the fiber.

By carefully designing the structure of the PCF, it's possible to manipulate dispersion properties, allowing for custom shaping of light pulses.

PCFs can concentrate light in small areas, enabling enhanced light-matter interactions and sensitivity in sensing applications.

PCFs can be designed to manipulate the polarization of light passing through them. By controlling the geometric arrangement of the microstructure, PCFs can selectively transmit or filter light based on its polarization state.

A diagram of a diagram of a diagram

Description automatically generated with medium confidence

Metamatrials:

Metamaterials manipulate light through their engineered structure, enabling control over fundamental optical properties like refraction, dispersion, polarization, and phase. For instance, magnetic metamaterials (MMs) are fabricated on the cross-section of optical fibers. These MMs interact differently with polarized light depending on whether it's on or off magnetic resonance. On resonance, they act as both grating and magnetic polarizers, altering the polarization state of radially polarized vortex beams while preserving their orbital angular momentum. This precise manipulation showcases how metamaterials offer novel ways to engineer light within optical systems, paving the way for advancements in communication, quantum information processing, and optical trapping.

A collage of images of a diagram

Description automatically generated

Figure 5 – (a) The schematic of the experimental setup to study radially polarized vortex beam interaction with the magnetic MM; (b) and (c) Calculated intensity profiles at the output for the cases of off- and on-resonance propagation, respectively; (d) and (e) Measured intensity profiles at the output for the cases of off- and on-resonance propagation, respectively

Liquid Crystal Q-Plates

A diagram of a spin-to-orbital conversion

Description automatically generated

Spatial Light Modulators:

Principle:

Liquid crystal on silicon spatial light modulators (LCOS SLMs) operate based on the principles of liquid crystal behavior and electro-optic effects. Liquid crystals are compounds with both liquid and crystalline properties, existing in mesophases with diffused molecular order. The nematic phase, commonly used in LCOS SLMs, features relatively low viscosity and allows molecules to reorient in response to an electric field.

The refractive index of liquid crystals varies depending on the orientation of the molecules. By applying an electric field, the orientation of the liquid crystal molecules can be controlled, leading to changes in the refractive index experienced by incident light. This phenomenon enables the modulation of light intensity and phase.

Diagram of a diagram of a waveform

Description automatically generated

A diagram of a waveform

Description automatically generated with medium confidence

In LCOS SLMs, various liquid crystal alignment structures determine how incident light is modulated. Twist nematic (TN) and vertically aligned nematic (VAN) structures are used for amplitude modulation, while the electrically controlled birefringence (ECB) structure is mainly employed for phase-only modulation. In TN mode, the orientation of liquid crystal molecules twists, affecting the polarization of incident light. VAN mode utilizes perpendicular alignment to achieve amplitude modulation. In ECB mode, the director of liquid crystal molecules switches between planar and homeotropic alignment, allowing for precise phase modulation.

The ability to precisely control the orientation of liquid crystal molecules determines the modulation capabilities of LCOS SLMs. Phase-only LCOS SLMs rely on the accurate manipulation of liquid crystal molecules' angles to achieve desired phase retardance, thus enabling precise phase modulation of incident light. The stability and resolution of phase modulation are crucial factors determined by the ability to control the orientation of liquid crystal molecules reliably.

In the fabrication process of phase-only LCOS SLMs, die-level assembly techniques are employed to ensure high-quality performance. These techniques involve precise alignment and assembly of components to achieve optimal functionality of the LCOS SLM device.

Advantages:

* High Spatial Resolution: SLMs offer high spatial resolution, allowing for fine control over the phase profile of the incident beam.
* Versatility: They are versatile devices capable of modulating various properties of light, including phase, amplitude, and polarization, making them suitable for a wide range of applications.
* Real-Time Reconfigurability: SLMs can be reconfigured rapidly and dynamically, enabling real-time adaptation to changing experimental conditions or application requirements.
* Adaptive Optics: They find applications in adaptive optics systems, where they compensate for optical aberrations and improve the performance of imaging systems.

Disadvantages:

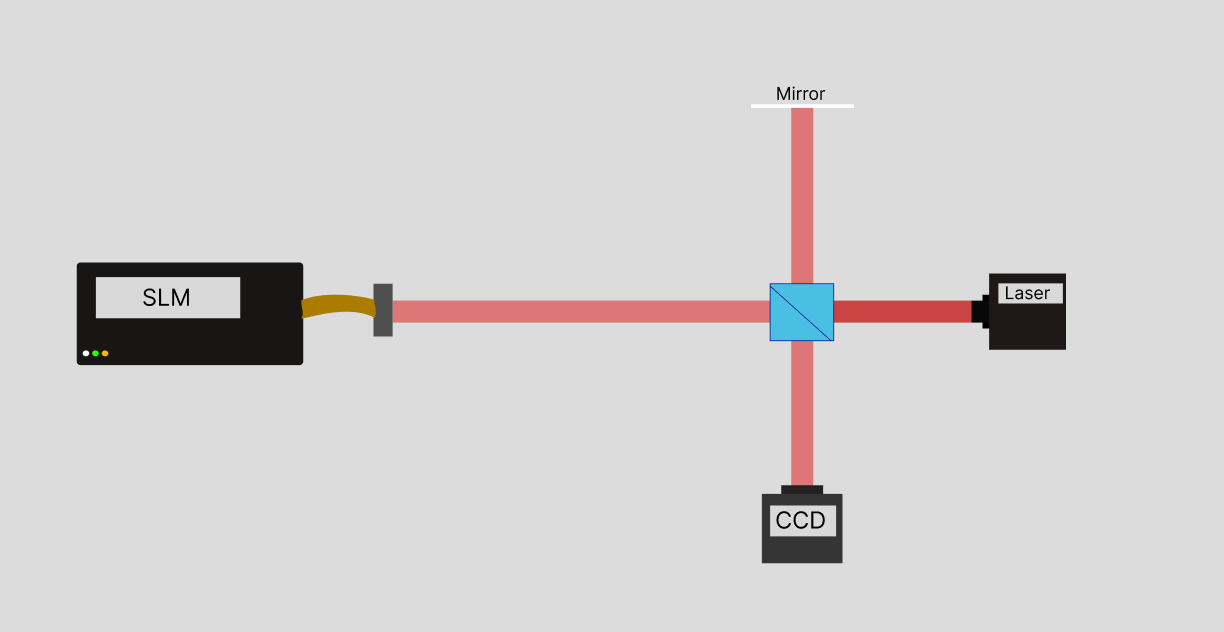
* Limited Phase Range: SLMs often have limited phase modulation range, particularly for high OAM modes, which can lead to truncation of the phase profile and reduced efficiency.
* Limited Phase Resolution: The phase resolution of SLMs may be insufficient for generating complex phase profiles required for high-quality OAM beams, leading to quantization errors and reduced beam quality.
* Losses and Efficiency: SLMs can introduce optical losses, scattering, and other imperfections, reducing the overall efficiency of beam generation and manipulation.
* Cost and Complexity: High-quality SLMs can be expensive, and their integration into optical systems may require complex alignment and calibration procedures.

Limitations:

* Pixel Pitch: The pixel pitch of SLMs imposes a limit on the achievable spatial resolution and phase modulation range, which can affect the quality of generated OAM beams, especially at higher orders.
* Speed: The response time of SLMs may limit their suitability for applications requiring high-speed beam modulation or dynamic reconfiguration.
* Calibration and Stability: SLMs require careful calibration to ensure accurate phase modulation and stability over time and environmental conditions.
* Optical Nonlinearity: Nonlinear optical effects in SLM materials can introduce distortions and nonlinear phase modulation, affecting the fidelity of generated OAM beams.

Setup and the GUI

Setup:



Alignment:

GUI image

To align this system, two distinct alignments are required.

The first alignment involves the laser and the center of the SLM. Initially, the mirror is covered and the alignment is coarsely performed with a red laser. For a more precise adjustment, a phase mask is sent, divided into two parts with values of 0 and 2π. The divisions are made horizontally for horizontal alignment and vertically for vertical alignment. It is important to observe two lines similar in intensity and size in the CCG.

The second alignment is performed with the mirror. For this, the obstacle in front of the mirror is removed. A red laser is used to centralize the beam with the beamsplitter and the CCG. Then, the laser is switched to 1555 nm for fine adjustment, aiming to observe the interference pattern.

As soon as the mask type is loaded, the generated phase mask appears in the “phase” field. Next to it, the “intensity - simulation” field, as the name suggests, is the simulation (as explained in the previous chapter) of what is expected to be observed after the beam propagation, considering the applied phase mask. This intensity serves as a comparison parameter with the results observed in the CCG.

Now, let’s translate this into English:

Once the mask type is selected, the generated phase mask appears in the “phase” field. Adjacent to it, the “intensity - simulation” field, as the name implies, is the simulation (as explained in the previous chapter) of what is expected to be observed after the propagation of the beam, considering the applied phase mask. This intensity serves as a comparison parameter with the results observed in the CCG

Laguerre-gaussian beams

GUI image

With the system aligned, we can proceed to manipulate the light beam as desired. The Laguerre-Gauss tab allows users to adjust the orders l and p, as well as the beam radius. The simulated result is displayed on the interface, showing how the beam will be modulated. The system then sends the corresponding phase mask to the Spatial Light Modulator (SLM), and the resulting beam pattern is captured by the Charge-Coupled Device (CCD) camera for analysis.

Hermite-gaussian beams

GUI image

The Hermite-Gauss tab enables users to specify the mode orders x and y, along with adjusting the scale. The interface shows the simulated result, and the corresponding phase mask is transmitted to the SLM. The output beam pattern is then captured by the CCD camera and displayed for verification and analysis.

Bessel-gaussian beams

GUI image

The Bessel-Gaussian tab allows the creation of Bessel-Gaussian beams by adjusting the order lll and scale. The system simulates the resulting beam profile and sends the appropriate mask to the SLM. The resulting beam pattern is captured by the CCD camera and displayed on the interface for further examination.

Common Adjustable Parameters

For Laguerre-Gaussian, Hermite-Gaussian, and Bessel-Gaussian beams, additional parameters such as aspect, angle, center, offset, and phase range can be adjusted. Moreover, users have the option to generate a grating mask with adjustable x grooves and y grooves, as well as the option to create a forked mask.

External masks

GUI image

For generating custom beam shapes, the External Masks tab allows users to upload their own phase mask designs. Once a mask is uploaded, it is previewed in the interface. The selected mask is then applied to the SLM, and the resulting beam profile is captured by the CCD camera. This feature provides flexibility for experimenting with a wide range of beam shapes beyond the standard Gaussian variants. Unlike the other tabs, external masks come ready-made, so parameters like aspect, angle, center, offset, phase range, grating mask, and forked mask are not applicable here.

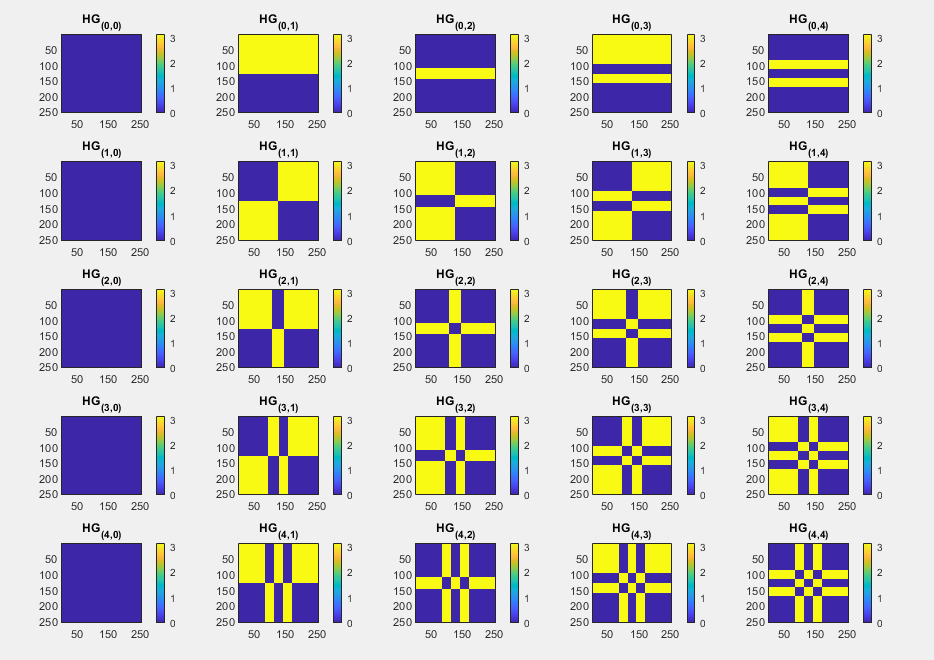
Results

Phase masks:

Laguerre-gauss phase:  
A screenshot of a computer generated image

Description automatically generated

Hermite-gauss phase:



bessel-gauss mask:

A group of images of a red and yellow circle

Description automatically generated with medium confidence

Experimental results

General:

Beams generation With Laguerre-gauss phase mask:

Beams generation With Hermite-gauss phase mask:

Beams generation With bessel-gauss phase mask:

OAM:

Without forked masks:



With forked masks:

A close-up of a black and white photo

Description automatically generatedA close-up of a black and white background

Description automatically generatedA black and white image of a zebra

Description automatically generatedA black and white image of a black circle

Description automatically generated

4 6 10 14

A close-up of a black and white image

Description automatically generatedA black and white image of a circle

Description automatically generatedA black and white image of a circle

Description automatically generatedA black and white image of a circle

Description automatically generated

16 16 20 30

When utilizing the setup with the mirror covered and applying a forced phase mask (grating = 5 + spiral with l=1), a diffraction pattern was observed on the CCD, as anticipated. The forced mask diffracted the beam into the -1ª ,1ª orders and 0ª. Since we are interested in the beam with OAM l=1, we will shift our SLM slightly to follow, in this case, the right diffraction order corresponding to 1ª order. As the number of divisions in the grating increases, the distance separating the different orders becomes larger. Therefore, this adjustment must be made step by step, as illustrated in Figure X. When the grating value reaches 20 or more, it becomes possible to observe the beam with OAM l=1 in the first diffraction order, manifesting as a perfect donut shape.

Simulation results:

General:

A screen shot of a graph

Description automatically generated

OAM:

Comparation with experimental

Conclusion

[Exjobbsframsida (arxiv.org)](https://arxiv.org/ftp/arxiv/papers/0905/0905.0190.pdf) paraxial eq, gaussian beam, maybe L\_G

[Fundamentals of Photonics (ysu.am)](http://lib.ysu.am/disciplines_bk/1e50d8144d6e0c3ffea3ae655684c626.pdf) Helmholtz

L-G, H-G and Bessel

[OAM beam generation in space and its applications: A review (sciencedirectassets.com)](https://pdf.sciencedirectassets.com/271471/1-s2.0-S0143816621X00127/1-s2.0-S0143816621003924/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEIT%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FwEaCXVzLWVhc3QtMSJHMEUCIHd%2F2kptGxGX9OueAxLOgRu3xWKa2DbXVfUljM3DlS%2FmAiEA%2B0WweXyDdAcrPgh0Gr%2BHxbWFYvT9JRpQh3tCBy1GIjcqvAUIvf%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FARAFGgwwNTkwMDM1NDY4NjUiDMD4KMqq91GhVFb7UCqQBbcJ%2B1AZEF%2BY%2BD5cdA6oZYYxJC%2BtvwjSx8xhdT9fWEPiW2b7jHIM7zlCC2LwiXyzsFaFmzccRGABkfS3qZZfC2mWrG422qzf6cvslZhpV0QEz5U6eiGqzmYVqMIGIeLXw%2BxdPhv37Kqgh1BBswjkkcSrR9tBruOd4UIUgmlBwd5pdr4c%2FNp14Ih5%2BoKYB2%2BfcpwlPXMiwQBeHiKYUW2VHrLwqrd9OCVytzudbAoTtBgs9g2%2Fqz6VVKHMyWlYmG2nnzQg%2FA%2B2wzSyx%2BVzbxXwxZPohrtjRBw0QyRYKE%2F7EcaF4YOnPhtIiqzKRnaelphWynyRn%2Bb3CG3%2F%2F5BmlZx6sHfI5O6UOk0qYQxYyMlBk8B0YeDAFss81%2Bm7zc4gQ99UIb6Dw7D1BmjnWe8NKT3oF%2FEznhz5VxCyYmaKOgCKAgQN0Q46uc3ztEQenskH03AmhNcA3r4muKuw3sZBuiQ11vdmlTTsBG0Rg5OZdzhAz92nbrQp%2BiI06xqFlCxFyjTsw5JfRTzUsE8dmF1u645Zdk3MyNYtLaVp%2FzE5SnuuAzWz4HvxVEu8pCDfZxQeORDrVYSPuS3c0mnrXMzeWZNn862xXsGc%2F84PlptZaEZ2hac3oy%2BHYC%2FA%2BboKbFsx2YwLn2%2Bf174GNlGziqzankUs%2FlWMGH7q5RINiXc4We%2FNnsr1ZIOKwyQR0o2X9MASXV%2BaOycqmmTWKAA3hf6U1TUdFzJ04Np5yU%2FPX6nbAo1k20WfwDvA1Nbk3ddNkOilNnGqdDSyNcPin%2FKc1KcVFF66ur1iy3y9Aj3ErhuclSb00W5SIIwIpM4IHgd4sMyahHMY0VQRRbTQd2uCMEBG9VHnaQ70vzUbBJEgiUWDl%2Fx5RUV3MJfK%2BbAGOrEBKdaMS8Ja4ifeHoDyaipb36fcr5LFahaVLBFt5DtCXA%2BHHhBzME04KwdPrKOfM9aVguhgXWyE6C0lLN10Na1HwFWkV72NUeSIbWerkSBLP332AvJYwkYWQuyVr4%2B1cc202In%2BrWm5xyoN9XspU1bVc0mpmMuZ11UqTegLiIOqudonU6Q%2FLTa2ps7YFCBkb%2BqYOFMZqGD5eB6o7G8hN3dMStcWht4rNnmjQqemnFKY9Elv&X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Date=20240416T120852Z&X-Amz-SignedHeaders=host&X-Amz-Expires=299&X-Amz-Credential=ASIAQ3PHCVTYT3TX7T7W%2F20240416%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Signature=b2486495ed6621fc57e8057fd35e1636015df0173ba6c6fa08bd8e226f2e23bd&hash=0451458168a4426d37e9478744562bc5e1e246aa4f9aac0a735fb17cf891cbe4&host=68042c943591013ac2b2430a89b270f6af2c76d8dfd086a07176afe7c76c2c61&pii=S0143816621003924&tid=spdf-186692b5-b4ef-4ab1-95d7-2f4de484f659&sid=b136733e7b9c5843697b64e050a615b4)