Frontiers in Computing and Intelligent Systems
ISSN: 2832-6024 | Vol. 14, No. 1, 2025

Exploration of Optical Vortex Preparation, Detection and Application based on Orbital Angular Momentum Characteristics

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Abstract: Optical vortices, as the core research object of singularity optics, are characterized by their spiral wavefront structure and determined photon orbital angular momentum. This property makes them irreplaceable in fields such as optical micro manipulation, quantum communication, biomedical and atomic optics. This article takes "principle preparation detection application" as the core framework to systematically analyze the optical vortex technology system. Firstly, it explains the physical essence of optical vortices, clarifies the spiral wavefront characteristics revealed by their optical field expressions, the "dark sky" structure caused by phase singularities, and the regulatory effect of topological charges on the direction and phase changes of spiral rotation; Secondly, in-depth analysis of the principles of mainstream preparation techniques such as geometric optical mode conversion, computational holography, spiral phase plate method, and liquid crystal spatial light modulator method is conducted, and the applicable scenarios and advantages and disadvantages of each method are clarified through multidimensional comparison; Furthermore, based on Maxwell's electromagnetic theory, the mathematical model of orbital angular momentum is derived, and the technical details and applicability of detection methods such as computational holography, interferometry (including plane wave interferometry, conjugate light interferometry, Young's double slit interferometry, Mach Zehnder interferometry), and porous interferometry are comprehensively reviewed; Finally, based on the application examples of optical vortices in optical tweezers (particle trapping and rotation), quantum secure communication (topological charge encoding), ultra cold atom confinement ("optical potential tube"), biological imaging and photodynamic therapy, etc., this paper points out the challenges of current high-power preparation bottlenecks, dynamic high-precision detection difficulties, and insufficient cross domain fusion, and looks forward to their development trends in high-power beam modulation, cross scale micro manipulation, multi-dimensional information encoding, etc., providing theoretical support and practical reference for related technology research and interdisciplinary innovation.

Keywords: Optical Vortex; Phase Singularity; Topological Load; Quantum Communication; Orbital Angular Momentum.

1. Fundamental Theory and Development of Optical Vortex

1.1. The Physical Essence and Core Characteristics of Optical Vortices

Optical vortices are a type of optical field with a special spatial phase distribution, characterized by two core properties: helical wavefronts and phase singularities. From the perspective of electromagnetic field theory, the optical field expression of optical vortices can be described as $u(\mathrm{r},\theta,z)=u_0(\mathrm{r},z)\mathrm{e}^{\mathrm{i}l\theta}e^{-\mathrm{i}kz}$(where $\mathrm{r}$is radial distance, $\theta$is azimuth angle, z is propagation distance, $u_0(\mathrm{r},z)$ is amplitude distribution, $k$is wave vector, $\mathrm{l}$and is topological charge).This expression reveals the key characteristic of optical vortices: the phase factor θ corresponding to the azimuth angle $e^{\mathrm{i}l\theta}$causes the wavefront to spiral around the propagation axis (vortex axis), with a phase change for each revolution around the vortex axis$2\pi l$, and the positive or negative of l determines the direction of spiral rotation (positive is counterclockwise, negative is clockwise). [1]

Phase singularity is another important indicator of optical vortices, referring to a special point in the optical field where the phase is uncertain - at this point, both the real and imaginary parts of the optical field are zero, resulting in the cancellation of light intensity due to interference, forming a "dark sky" structure.This structure endows optical vortices with unique physical advantages: the central dark spot can avoid light damage to trapped particles, and the circular light intensity distribution provides conditions for stable confinement of particles, making them irreplaceable in scenarios such as biological sample manipulation. In addition, the "dark sky" characteristic of optical vortices is accompanied by no diffraction effect, which means that the transverse spot size of the beam remains stable during propagation. This characteristic makes it of significant application value in long-distance particle waveguides, atomic optics experiments, and other fields. [2-3]

1.2. The Development Process and Key Breakthroughs of Optical Vortices

The origin of the study of optical vortices can be traced back to the 19th century, and after more than a hundred years of development, it has gradually moved from phenomenon discovery to theoretical improvement and technological application. Its development process can be divided into four key stages:

1.2.1. Phenomenon Discovery Stage (1930-2060s)

The research in this stage focuses on the observation and preliminary analysis of optical anomalies. In the 1830s, British scientist *Airy* first observed anomalous halos outside the focal plane of a lens in experiments, which became the starting point for optical vortex research - subsequent studies have shown that this anomalous halo is essentially an early observed form of optical vortices. In 1919, *Ignatovskii* conducted mathematical analysis on the anomalous halos observed by Airy, and preliminarily explored the correlation between the phase distribution of the light field and the formation of halos;In 1959, *Richards* and *Wolf* further studied anomalous halos from the perspective of energy flow and discovered a special energy rotation phenomenon near the halos;In 1967, *Boivin, Dow*, and *Wolf* confirmed through precise experiments that this energy rotation originates from a vortex structure that rotates in a straight line near the focal plane, and for the first time confirmed the existence of vortex phenomena in the optical wave field. During the same period, *Braunbek* and *Laukien* also observed similar vortex structures in the interference field in 1952, providing experimental evidence for the universality of optical vortices. [4]

1.2.2. Theoretical Foundation Stage (1970s-1980s)

The 1970s was a critical period for the breakthrough of optical vortex theory, with core progress focused on the essential understanding of phase singularities and the proposal of the idea of optical vortex generation.In 1974, *Nye* and *Berry* published groundbreaking research in *Proceedings of the Royal Society A*, which theoretically proved for the first time that phase defects are the fundamental cause of optical vortices - when there are phase discontinuous defect points in the light field, the wavefront will form a spiral structure around that point, thereby generating optical vortices.This discovery reveals the physical essence of optical vortices, driving the academic community from "phenomenological observation" to "theoretical analysis".

Afterwards, *Bryngdahl* and *Lee* proposed the innovative idea of actively introducing phase singularities in smooth wavefronts in 1978, providing a core theoretical direction for the artificial preparation of optical vortices;In 1979, *Vaughan* and *Willetts* conducted numerical simulations and experimental verification to analyze in detail the phase structure and propagation law of optical vortices, and established a quantitative correlation between topological charges and helical wavefronts;In 1981, *Baranova* discovered vortex structures in speckle fields, *while Harris* utilized the vortex characteristics in speckle fields to obtain scattering medium information, expanding the research scope of optical vortices and proving their potential value in the field of information extraction.

1.2.3. Discipline Establishment Stage (late 1980s to 1990s)

1989 was a milestone year in the study of optical vortices - *Coullet* et al. published a paper in *Physical Review Letters*, formally proposing the term "optical vortex" for the first time and analyzing the formation mechanism of vortices in laser cavities using *Maxwell Bloch* theory.They found that in a stable laser field with a high threshold voltage, a phase singularity with zero electric field strength can exist for a long time, and the phase around the singularity exhibits periodic changes. This state, similar to a superfluid vortex, is defined as an "optical vortex".This study not only provides a clear disciplinary definition for optical vortices, but also confirms their stability in nonlinear optical systems, marking optical vortices as an independent research branch of modern singularity optics.

In 1992, *Allen* et al. published another landmark paper in *Physical Review Letters*, which rigorously theoretically demonstrated the orbital angular momentum carried by each photon in a phase factor beam (i.e. optical vortex) under paraxial propagation conditions.This conclusion lays the core theoretical foundation for the application of optical vortices, making the academic community aware of their potential in fields such as angular momentum transfer and particle manipulation.In the same year, *Swartzlander* observed optical vortex solitons in self focusing nonlinear *Kerr* media, proving that optical vortices can propagate stably in nonlinear systems and expanding their research dimensions;In 1994, *Barnett* and *Allen* further confirmed that even under non paraxial propagation conditions, the orbital angular momentum of optical vortices remained$l\hbar$, perfecting the theoretical system of orbital angular momentum.

1.2.4. Application Expansion Stage (late 1990s to present)

Since the late 1990s, research on optical vortices has moved from theory to practice, with core advancements focused on breakthroughs in application technology and multi domain penetration.In 1995, *He* et al. used computational holography to generate optical vortices, successfully trapping and manipulating micrometer sized copper oxide particles, and experimentally verifying the transfer of orbital angular momentum of optical vortices to particles for the first time;In 1996, *Simpson* developed the "optical wrench" technology based on this principle, which achieved precise rotation of particles by regulating the topological charge of optical vortices, providing a new tool for dynamic manipulation of microscopic objects such as biological cells and colloidal particles;At the same time, *Gahagan* and *Swartzlander* achieved three-dimensional optical confinement of high refractive index (such as glass microspheres) and low refractive index (such as air bubbles) particles, demonstrating the applicability of optical vortices in complex particle manipulation scenarios. [5]

In the field of atomic optics, *Bazhenov* first proposed in 1992 to use the "dark sky" beam of optical vortices as a "potential tube" to bind ultracold atoms. Subsequently, researchers developed various magneto-optical potential wells based on this idea, successfully achieving long-term confinement and manipulation of ultracold atoms, providing key technical support for atomic clocks, quantum entanglement experiments, and so on.After entering the 21st century, the maturity of preparation technologies such as liquid crystal spatial light modulators and high-precision spiral phase plates has further promoted the application of optical vortices in quantum communication (topological charge encoding), biomedical (cell non-destructive manipulation), laser processing (circular spot cutting) and other fields, making it one of the research hotspots in modern optics.

1.3. Application Fields and Value of Optical Vortex

The unique physical properties of optical vortices make them irreplaceable in multiple disciplinary fields, covering basic research, technological development, and industrial applications. Specifically, they can be divided into the following five directions: [6]

1.3.1. Optical Micro Manipulation Field

Optical micro manipulation is one of the most mature application fields of optical vortices, based on its two major characteristics of orbital angular momentum transfer and "dark sky" structure.In the biomedical field, traditional optical tweezers technology uses the gradient force of Gaussian beams to trap particles, but strong central light can easily cause light damage to biological samples such as cells and organelles;The "dark sky" structure of optical vortices can avoid excessive central light intensity, while the gradient force generated by the circular light intensity distribution can stably bind particles, combined with orbital angular momentum transfer to achieve particle rotation and three-dimensional movement.For example, researchers have successfully achieved non-destructive confinement and rotation of red blood cells using topological charge $l = 3$ optical vortices, providing tools for blood cell morphology analysis and intracellular material transport research.

In colloid science and materials engineering, optical vortices can be used to manipulate the assembly of nanoparticles - by controlling the topological charge and light intensity distribution, nanoparticles can be guided to align along a circular trajectory to prepare functional materials with helical structures;In addition, the "optical wrench" technology can achieve precise rotation of micro components in microelectromechanical systems (*MEMS*), such as driving micro gears and adjusting micro lens angles, providing non-contact control solutions for the assembly and debugging of micro devices.

1.3.2. Quantum Information and Communication Field

The topological charge of optical vortices has integer properties (l being integers), and the optical fields corresponding to different topological charges are orthogonal to each other, making it an ideal carrier for quantum information encoding. In quantum secure communication, information can be encoded as a combination of different topological charges. Due to the orthogonality of topological charges, eavesdroppers find it difficult to obtain information without disrupting the quantum state, significantly improving communication security.In addition, the multi value nature of topological charges can significantly enhance the information encoding capacity - traditional polarization encoding can only achieve binary encoding, while topological charge encoding can achieve multi base encoding, providing a technical path for high-density quantum communication.In the field of photon computing, the topological charge of optical vortices can serve as a carrier for logical operations - by designing specific optical components (such as phase modulators, interferometers), logical operations between different topological charges (such as "AND", "OR", and "NOT") can be achieved, constructing all-optical logic gates and providing support for the development of high-speed photon computers.

1.3.3. Atomic and Molecular Optics

The "dark sky" structure and non diffractive properties of optical vortices make them an ideal tool for trapping ultracold atoms.In atomic physics experiments, ultracold atoms (with temperatures close to absolute zero) are extremely sensitive to light damage. The central strong light of traditional Gaussian beams can easily cause atomic heating, while the central dark spot of optical vortices can avoid this problem. At the same time, the potential well formed by the circular light intensity distribution can stably bind ultracold atoms.For example, researchers use high-order *Bessel* beams (a special type of optical vortex) to construct "optical potential tubes" to achieve long-term confinement of rubidium atoms, providing a stable atomic source for atomic interferometers, *Bose Einstein condensation (BEC)* experiments, and other applications.

In the field of molecular optics, optical vortices can be used to study the rotational dynamics of molecules - by placing molecules in an optical vortex field, molecules absorb the orbital angular momentum of photons and produce rotation. By using spectroscopic techniques to measure the rotational frequency of molecules, key parameters such as rotational inertia and intermolecular interactions can be obtained, providing a new method for molecular structure analysis.

1.3.4. Biomedical Field

In addition to optical micro manipulation, the application of optical vortices in the biomedical field also includes biological imaging, pathological detection, and other directions. In biological imaging, the spiral phase structure of optical vortices can change the spatial coherence of the light field. By designing a specific vortex imaging system, phase imaging of transparent biological samples (such as cells and tissue slices) can be achieved, and the refractive index distribution information of the samples can be obtained without staining treatment, avoiding damage to the samples by chemical staining. For example, quantitative phase imaging technology based on optical vortices has been used for detecting abnormal red blood cell morphology. By analyzing the differences in phase distribution, red blood cell deformation caused by diseases such as anemia and malaria can be quickly identified.

In the field of photodynamic therapy, the circular light intensity distribution of optical vortices can achieve precise irradiation of tumor tissue - after injecting photosensitive drugs into the tumor area, the circular light spot of optical vortices is used to excite photosensitive drugs, generate singlet oxygen to kill tumor cells, and avoid radiation damage to the central normal tissue, thereby improving the accuracy and safety of treatment. [7-8]

1.3.5. Interdisciplinary Research Fields

The topological structure of optical vortices provides important research tools for interdisciplinary fields such as astronomy, superfluid physics, and topological mathematics. In astronomy, the light field emitted by celestial bodies (such as stars and galaxies) may generate vortex structures due to gravitational lensing effects. By detecting the topological charge and distribution of these vortices, key parameters such as the mass distribution and gravitational field strength of celestial bodies can be inverted, providing auxiliary means for dark matter detection and gravitational wave research; In superfluid physics, optical vortices and vortex structures in superfluids (such as helium-4 superfluids) have similar topological characteristics. By comparing the formation mechanisms and dynamic behaviors of the two, we can deepen our understanding of quantum fluid mechanics;In the field of topological mathematics, the spiral structure and phase singularity of optical vortices can serve as physical examples of topological spaces, providing intuitive physical models for abstract concepts such as "homology groups" and "genus" in topology, and promoting the combination of mathematical theory and physical experiments.

2. Angular Momentum Theory of Optical Vortices

It is a recognized scientific fact that light has momentum, and the magnitude of its momentum is closely related to its intensity. This characteristic has important application value in multiple fields. Normally, the orbital angular momentum of light is related to the polarization state of its beam.As early as the 1830s, scientist *Beth* discovered that the orbital angular momentum of light can be transmitted to matter during rotation;In depth research has shown that the root cause of this phenomenon lies in the special spiral wavefront structure possessed by the optical vortex field itself, as well as the determined orbital angular momentum it carries. [9-11]

2.1. Orbital Angular Momentum Characteristics of Optical Vortices

Electromagnetic radiation carries both momentum and energy, with momentum being further divided into two categories: linear momentum and angular momentum. The total angular momentum of an electromagnetic field can be divided into two parts, one is the spin angular momentum (S) related to polarization, and the other is the orbital angular momentum (L) related to spatial phase distribution. In 1936, *Beth* was the first to discuss the issue of angular momentum of circularly polarized light;In 1992, *Allen* et al. proposed that optical vortices have a definite orbital angular momentum under paraxial propagation conditions, which provided a key impetus for the study of optical vortices.

In the paraxial propagation scenario, a light field with a spiral wavefront (i.e. optical vortex) has photons with orbital angular momentum inside; And circularly polarized beams possess spin angular momentum.Even under non paraxial propagation conditions, optical vortices still retain orbital angular momentum.For linearly polarized light, the correction term value is zero at this time, and only the orbital angular momentum exists. Its relationship with other physical quantities also returns to the state of paraxial propagation.Optical vortices with spiral wavefronts have a definite orbital angular momentum. When there is a circularly polarized state, it also possesses additional spin angular momentum.Both of these angular momenta can potentially interact with an object through the transfer of momentum, leading to displacement and velocity changes in the object.This feature is of great significance and has important potential application value in the fields of life sciences, basic physics, precision measurement, and related technologies.

2.2. A Typical Method for Measuring the Angular Momentum of Optical Vortex Orbits

2.2.1. Computational Hologram Method

Weihs et al. proposed a method for measuring the orbital angular momentum of optical vortices using computational holograms, and the experimental setup is shown in Figure 1.

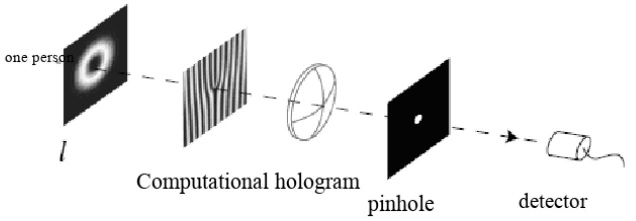


Figure 1. Measurement of the orbital angular momentum of optical vortices using the holographic method

2.2.2. Optical Vortex and Plane Wave Interference Method

The interference method introduces a reference beam to interfere with a vortex beam, and determines the topological charge (orbital angular momentum) and position of the optical vortex by analyzing the shape of the interference fringes. The vortex beam can be expressed as:

$$o(x,y) = u_0 e^{jl\theta} \tag{1}$$

For the case where the reference wave is a plane wave:

$$r'(x,y) = r_0 e^{jkx} \tag{2}$$

The intensity distribution form of interference fringes is:

$$I(x,y) = |o(x,y) + r(x,y)|^2$$

$$= u_0^2 + r_0^2 + u_0 r_0 \cos(l\theta - kx) \tag{3}$$

At $\cos(l\theta - kx) = -1$that time, that was

$$l\theta - kx = (2n+1) \tag{4}$$

Dark stripes appear. If the test beam contains singularities, dislocations or bifurcations will appear at the endpoints of an interference fringe, and the location of the dislocation indicates the position of the singularity. The number of topological charges of the spiral wavefront can be determined based on the number of bifurcations, and the sign of the topological charge can also be determined based on the direction of the bifurcations. The number and direction of bifurcations correspond one-to-one with the size and sign of the topological charge, so the measurement of the orbital angular momentum of the optical vortex can be achieved based on the interference pattern between the plane wave and the optical vortex.

2.2.3. Optical Vortex and its Conjugate Optical Interference Method

The experimental setup is shown in Figure 2.

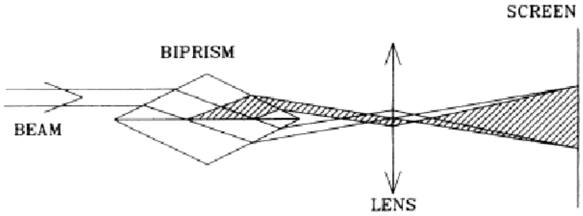


Figure 2. Schematic diagram of experimental setup for optical vortex and its conjugate mutual interference

The amplitude of a wave can be expressed as:

$$E = E_0 r^{|m|} e^{-j2\alpha r} e^{\pm jm\theta} \tag{5}$$

Among themE_0, and a are constants that determine the light intensity and beam parameters, respectively. When it interferes with its conjugate light at a small angleα, the synthesized amplitude

$$E = (e^{jm\alpha} e^{j\alpha x} + e^{-jm\alpha} e^{-j\alpha x}) E_0 r^{|m|} e^{-j2\alpha r} \tag{6}$$

For high-order modes, light intensity

$$I = I_0(r) \cos(\alpha x \pm m\theta) \tag{7}$$

The computer simulation results based on theoretical analysis are shown in Figure 3.

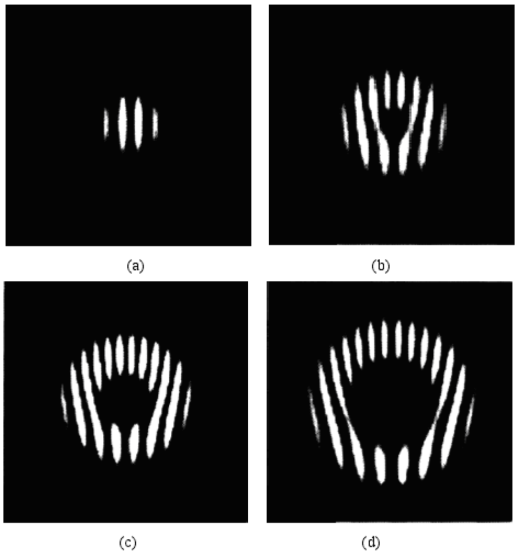


Figure 3. Simulation results of mutual interference between optical vortex and its conjugate light

Comparing the number of bright spots above and below the interference pattern, it is easy to find that the extra number is exactly twice the number of topological charges in the optical vortex.Therefore, this method can be used to measure the orbital angular momentum of optical vortices.

2.2.4. Yang's Double Slit Interferometry Method

Sztul et al. proposed using the Young's double slit interference method to measure the orbital angular momentum of LG beams.The experimental setup is shown in Figure 4.The distance between the double slits is 2a, and the distance between the plane where the double slits are located and the observation screen is d.

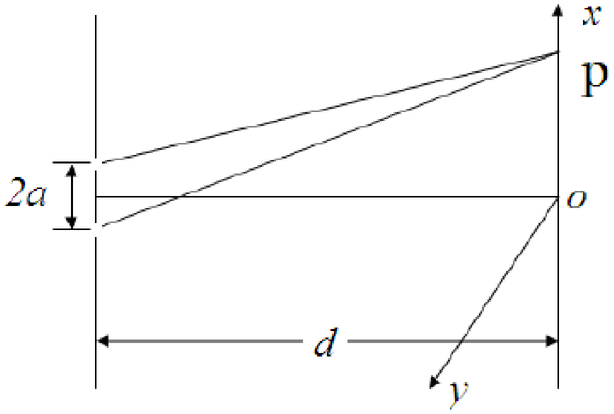


Figure 4. Schematic diagram of Yang's double slit interference experiment

We simulated the light intensity distribution on the screen when a vortex beam with a phase singularity falling at the center of the double slit is incident using a computer.Firstly, consider the topological charge$l = 0$, which is the case when a plane wave is directly incident.At this point, the wavefront distribution incident on the double slit is still a plane.Interference fringes are a series of straight lines that are parallel to each other and form a distribution of light and dark intervals.

When the topological charges are respectively$l = +1$, the interference fringes move by about one fringe, that is, the bright fringes (or dark fringes) at the bottom will roughly correspond to the bright fringes (or dark fringes) at the adjacent level at the top.When the topological charges are$l = -1$, the interference fringes move in the opposite direction by one fringe (opposite to$l = +1$).

When the topological charges $l = +2$ are equal, the interference fringes move by two fringes, that is, the bright fringes (or dark fringes) at the bottom correspond to the bright fringes (or dark fringes) near the second level at the top.The direction of stripe movement is related to the sign of the topological charge value.

The value of topological charge in vortex beams has a significant impact on the interference fringes generated when vortex beams undergo double slit interference. For an unknown topological charge, the value of the topological charge can be obtained by observing the distribution of interference fringes in the interference field.

However, for the case of large topological loads, the far-field interference pattern of the Young's double slit experiment becomes difficult to distinguish. By analyzing the near-field Young's double slit interference pattern, the orbital angular momentum of optical vortices with larger topological charge values can be better measured. [12]

3. Common Methods for Generating Optical Vortices

Optical vortex is a unique optical field distribution with many novel physical properties, which has been extensively studied and applied in fields such as laser optics, molecular optics, micro manipulation, and biomedical research. It has also received widespread attention from the scientific community. However, it should be clarified that all applications of optical vortices are based on a core foundation, namely the generation of optical vortices. Currently, the majority of ordinary lasers output Gaussian beams, and how to convert Gaussian beams into vortex beams has become a key issue. With the development of technology, people's understanding of optical vortex fields continues to deepen, and their application research has also attracted wider attention.In recent decades, researchers from various countries have proposed various methods for generating optical vortices, among which the most core and widely used are mainly four types: geometric optical mode conversion method, computational holography method, spiral phase plate method, and spatial modulator method.The following text will provide a brief introduction to these common methods.

3.1. Common Methods for Generating Optical Vortices

3.1.1. Geometric Optical Mode Conversion Method

The geometric optical mode conversion method can generate vortex beams in two forms. The first is to use a cylindrical lens system to convert Hermite Gaussian beams to Laguerre Gaussian beams to generate vortex beams. The second is to use a conical mirror system to generate high-order *Bessel* beams.Among them, the first form is more common, as shown in Figure 5.*A Bessel* beam is a type of beam with diffraction invariant properties, and all high-order *Bessel* beams except for zero order contain a phase factor$e^{il\theta}$ and are vortex beams.

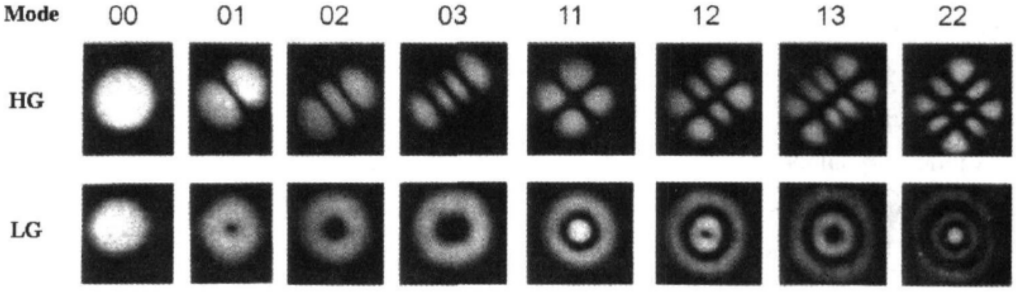


Figure 5. Hermite Gaussian beam and corresponding Laguerre Gaussian beam

3.1.2. Spiral Phase Plate Method

Spiral phase plate (SPP) is a pure phase optical element, whose rotation azimuth is proportional to the optical thickness, and the transmittance function is proportional to$e^{il\theta}$, where$l$ is the topological charge of the spiral phase plate.When a plane wave passes through a spiral phase plate, it is endowed with phase characteristics. The beam has a phase singularity and a spiral wavefront structure, which is called an optical vortex field.The ideal spiral phase plate has a continuous and smooth phase, but due to the scarcity of processing equipment and limitations in manufacturing processes, the spiral phase plates used in reality are mostly stepped spiral phase plates, with surfaces similar to rotating steps.

When the laser beam passes through a transparent spiral phase plate. Due to the difference in thickness of the spiral phase plate, the distance traveled by the beam is also different, resulting in the appearance of optical path difference and phase change, and the emergence of a new phase factor for the outgoing beam. In an ideal situation, the thickness of the spiral phase plate is proportional to the rotation azimuth angle. Figure 6 shows the principle diagram of generating optical vortices using the spiral phase plate method.

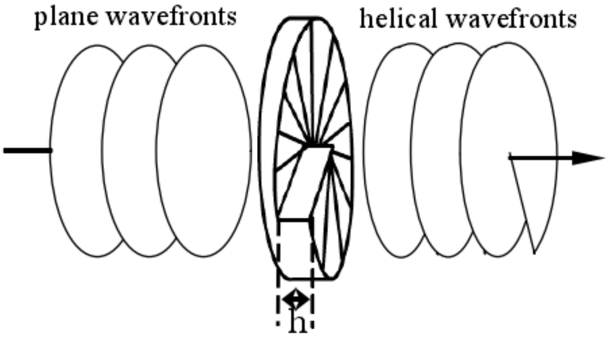


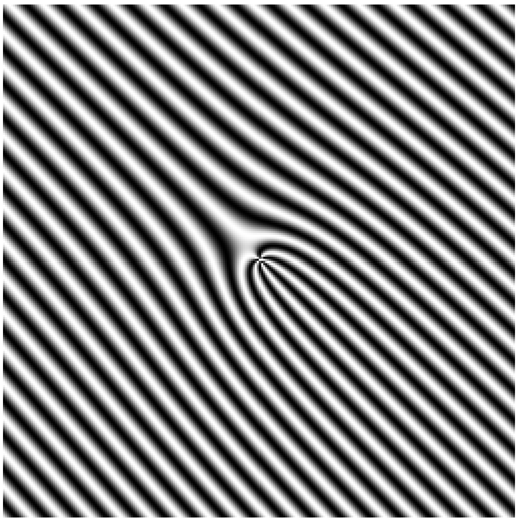
Figure 6. Principle of wavefront transformation using spiral phase plate method

3.1.3. Computational Holography

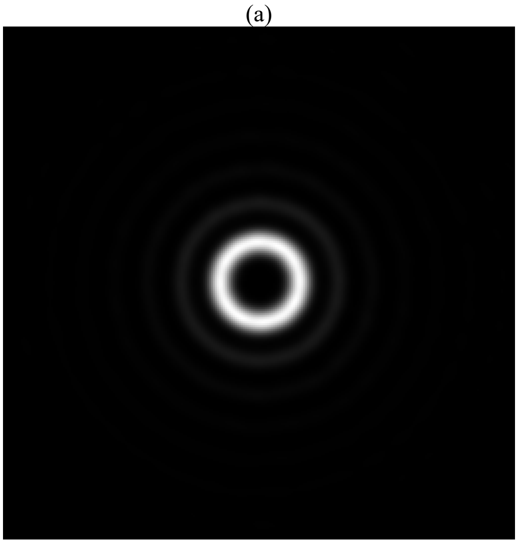
The computational holography method is an effective means of generating vortex beams, and its core process is to generate the interference pattern between the target light and the reference light through a computer, and then record and produce the pattern into a holographic grating or hologram.In 1992, Bazhenov successfully generated vortex beams with controllable size and topological charge using computational holography for the first time. [13]

The principle of this method is to utilize the characteristic that the interference fringes of spiral waves and plane waves exhibit a dislocation grating structure, and to obtain vortex beams using computer-generated holograms.With the gradual promotion of the concept of optical vortices, computational holography has also been widely applied in practice.

The computational holography method introduces phase singularities in the incident beam to generate optical vortices.Due to the existence of phase singularities, holograms become periodic gratings with central dislocations, and the number of dislocations is the topological charge of the optical vortexWhen a fundamental mode Gaussian beam is used to illuminate a hologram, the reconstructed first-order diffracted light wave is an optical vortex containing $e^{il\theta}$a phase factor. Figure 7 (a) is a typical computational hologram used to generate optical vortices, where $l = 5$Figure 7 (b) is the optical vortex pattern generated using the hologram.



(a)



(b)

Figure 7. Interference type computational hologram and generated optical vortices

3.1.4. Spatial Modulator Method

Liquid crystal spatial modulator is a device that modulates the spatial distribution of light waves.It can achieve spatial modulation of some or all of the physical quantities such as amplitude, phase, and polarization state of the output light field according to the requirements of the input control signal. It controls the phase map displayed on the spatial light modulator through computer control, thereby controlling the position, size, and topological charge of the optical vortex generated. It can also adjust the vortex beam in real time to achieve optical micro manipulation and mixed processing of light, machine, and electricity.

In 2002, *Jennifer E. Curtis* et al. proposed a method of generating optical vortices using liquid crystal spatial light modulators.In the experiment, the spiral phase diagram is displayed on a spatial modulator. When the incident beam passes through the spatial modulator, the spiral phase structure will modulate the phase of the incident beam, causing it to be superimposed with a phase factor$e^{il\theta}$. This way, an optical vortex containing the spiral phase factor can be obtained at the focal plane behind the lens. Figure 8 shows the experimental setup for generating optical vortices using a spatial modulator.

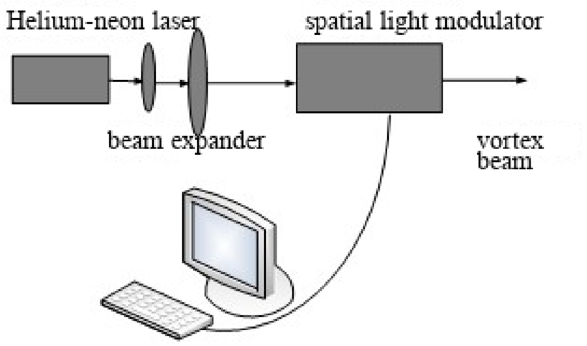


Figure 8. Experimental setup diagram of optical vortex generated by spatial light modulator

3.2. Comparison of Advantages and Disadvantages of Common Methods for Generating Optical Vortices

The geometric optical mode conversion method has the advantages of high efficiency and high beam purity when generating optical vortices. However, this method also has obvious limitations, such as high requirements for the production of core optical components and complex optical mode conversion systems. The required incident beam, the Hermite Gaussian beam, is also difficult to obtain, resulting in insufficient flexibility in practical applications.

The core principle of computational holography is to create a hologram by interference fringes formed by reference light and target light, and then generate optical vortices with parameter matching from the hologram, which has a relatively wide range of applications. However, this method has issues such as low holographic diffraction efficiency, susceptibility to display performance and resolution, and is therefore only suitable for generating low order vortex beams.

The advantage of the spiral phase plate method lies in its high conversion efficiency and ability to adapt to high-power laser beams; Especially when dealing with high-power lasers or applied to small instruments, it has value that cannot be replaced by other methods.However, due to the scarcity of processing equipment and strict manufacturing processes, the preparation of high-quality spiral phase plates is difficult, which limits the flexibility of this method in practical applications.

The prominent advantage of the spatial modulator method is its strong flexibility, which can flexibly adjust various parameters of the vortex beam according to needs, and can also achieve optical, mechanical, and electrical hybrid processing of the beam. However, this method has obvious shortcomings, as the spatial light modulator has certain limitations on the energy of the incident beam and cannot handle high-power laser beams.

Due to the advantages and disadvantages of each of the above methods, we should choose a reasonable method for generating optical vortices according to our needs

4. Technological Challenges and Future Development Directions

Although significant progress has been made in optical vortex technology, it still faces challenges in high-power preparation, high-precision detection, and cross domain fusion. In the future, breakthroughs are needed in materials, processes, and algorithms.

4.1. Existing Technological Challenges

4.1.1. The Bottleneck of High-Power Optical Vortex Preparation

At present, the damage threshold of liquid crystal spatial light modulators is relatively low and cannot adapt to high-power lasers above kilowatts; Although the spiral phase plate can withstand high power, the machining accuracy limitation leads to uneven distribution of vortex light intensity generated. In addition, high-power lasers are prone to topological charge distortion during propagation due to nonlinear effects in the medium, which affects beam quality.

4.1.2. Difficulties in Dynamic High-Precision Detection

In existing detection technologies, it is difficult to balance real-time and accuracy: although plane wave interferometry can provide real-time imaging, it is sensitive to interference; The Mach Zehnder interferometer method has high accuracy, but requires multi-level modulation and slow detection speed. In addition, there is still a lack of mature methods for detecting fractional topological charge vortices, which have important application value in nonlinear optics, but existing technologies cannot accurately distinguish their topological charges.

4.1.3. Insufficient Integration of Cross Domain Applications

In the biomedical field, the penetration depth of optical vortices is limited and cannot be used for deep tissue manipulation; In the field of quantum communication, topological charge states are easily affected by mode dispersion in long-distance fiber transmission, leading to state distortion;In the field of industrial processing, the energy distribution of the circular light spot of optical vortices is uneven, making it difficult to achieve uniform cutting.

4.2. Future Development Direction

4.2.1. Innovation in High-Power and High-Precision Preparation Technology

On the material level: Develop spiral phase plates with high thermal conductivity and high damage threshold materials such as diamond and sapphire to enhance high-power tolerance; Develop liquid crystal spatial light modulators based on two-dimensional materials such as graphene to reduce light absorption losses.

On the process level, femtosecond laser direct writing technology is used to process continuous spiral phase plates, controlling phase modulation errors within $\lambda/20$ a certain range; Developing 3D printing technology to prepare micro nano scale conical mirror arrays, achieving simultaneous generation of multiple *high-power* Bessel beams. [14]

4.2.2. Breakthrough in Dynamic and Multi-Dimensional Detection Technology

Hardware level: Develop integrated detection chips, integrating porous interferometers and *CCD* sensors on silicon-based chips to achieve miniaturization and rapid detection; Develop a single photon detector array to enhance the detection sensitivity of weak intensity vortices.

At the algorithmic level, deep learning algorithms are introduced to train a mapping model between interference patterns and topological charges, achieving automatic recognition of fractional topological charges; Develop real-time phase unwrapping algorithm to shorten the processing time of detection data.

4.2.3. Cross Disciplinary Application Technology Expansion

Biomedical field: Combining near-infrared optical vortices (penetration depth>10 mm) with photoacoustic imaging technology to achieve precise manipulation and dynamic observation of deep tissue cells; Develop a photodynamic therapy system based on optical vortices, utilizing a circular light spot to achieve uniform irradiation of tumor tissue.

In the field of quantum communication, design a topological charge polarization composite encoding system that utilizes the multivalued nature of topological charges and the binary nature of polarization to further enhance information capacity; Develop anti dispersion fibers to reduce distortion of topological charge states during long-distance transmission.

In the field of industrial processing, topological charge superposition technology is used to generate flat topped circular light spots, achieving uniform cutting of metal sheets; Develop laser cleaning technology based on optical vortices, using circular light intensity to remove surface micro pollutants and avoid damaging the substrate.

4.3. Summary

As the core research object of modern singularity optics, optical vortices have demonstrated irreplaceable value in fields such as optical micro manipulation, quantum communication, and atomic optics due to their unique spiral wavefront structure and orbital angular momentum characteristics. This article constructs a complete technical system of "principle preparation detection application" by reviewing the basic theory, preparation technology, and detection technology of optical vortices, and clarifies the applicable boundaries of each technology through multidimensional comparison. Currently, optical vortex technology is at a critical stage of transitioning from basic research to practical applications, facing three major challenges: high-power preparation, dynamic detection, and cross domain fusion. In the future, with the innovation of material technology, breakthroughs in detection algorithms, and expansion of application scenarios, optical vortices are expected to achieve disruptive applications in fields such as information technology, national defense, and biomedical science, becoming an important driving force for promoting interdisciplinary innovation.

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