Vortex beam and its application in optical tweezers

Chenliang Liu
Key Laboratory of Non-destructive Test (Ministry of Education), Nanchang Hangkong University, Nanchang, Jiangxi, 330063, China
lcl_will@163.com

Abstract. Vortex beams are beams with a spiral phase distribution and zero central light intensity. In recent years, it has been widely studied and applied. This article first analyses the characteristics of the vortex beam from a theoretical perspective, and then introduces the application of the vortex beam to optical tweezers.

1. Introduction
In recent years, the research and application of vortex beams have attracted more and more attention. This phenomenon has been studied since Airy discovered that an odd ring would form on the focal plane of the lens in the 19th century [1]. A. V. Volyar [2] Point out that the basic unit of transverse optical vortex has phase singularity. This is the first time that this phenomenon has been explained with optical vortex. The vortex beam has a spiral wave surface. After passing through a lens with a high numerical aperture, it can be focused into a ring-shaped light trap, which can be applied to the fields of particle capture and rotation [3]. And the orbital angular momentum carried by beams with different topological charges is also different [4], the orbital angular momentum carried by the vortex beam can be transmitted to the particles to drive the particles to rotate. Vortex beam with zero center intensity can be used to generate optical tweezers, and can also capture and mobile micron and submicron particles. So it has a wide range of applications in optical information transmission, optical manipulation, optical and tweezers, etc [5-7]. Based on the complexity and diversity of the characteristics of the vortex beam, its research has very important scientific significance and deserves our in-depth and extensive research.

2. Theory
Vortex beams are beams with a spiral phase distribution [8]. Each photon in the beam carries the orbital angular momentum of $lh$, where $l$ is called the topological charge. In the transmission along the optical axis, its wave front is spiral vortex, which rotates and propagates around the optical axis, and has a dark nucleus with zero light intensity in the center [9-10]. Orbital angular momentum carried by vortex beams, related to topological charge. Therefore, according to the number of different topological charge, the numerical expression of the vortex beam propagating along the z-axis can be simplified in cylindrical coordinates as:
Figure 1. The distribution of vortex light in space when the topological charge is 1

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

Where \( E \) represents the electric field of the vortex beam somewhere in the cylindrical coordinates, \( E_0 \) represents the amplitude intensity, \( k \) is the wave number, the size is \( k=2\pi/\lambda \), \( l \) represents the number of topological charges, and \( \theta \) is the azimuth. The spiral phase of vortex light is determined by the term \( \exp(-il\theta) \) in the formula (1).

From the results shown in the Fig. 2, when the topological charge integer is \( n \), its phase changes from zero to \( 2n\pi \) within a period, and with the number of topological charges increases, the dark core area at the center of the vortex beam also gradually increases. We can adjust the size of the dark core by adjusting the size of the topological charge, which is of great significance for the application of vortex beams to optical tweezers. The research on topological charge number measurement of vortex beams is mainly limited to integer-order vortex beams, but the study of fractional-order vortex beams is also of great significance. Because unlike the integer symmetrical vortex beam circularly symmetrical light intensity distribution, a gap will appear on the bright ring of the fractional vortex beam [11]. The fractional value of the vortex beam can make it have a stronger coding ability, this makes the vortex beams have a broader development prospects.

Figure 2. Phase and light intensity distribution under different topological loads. Fig (a), (b), (c), (d), (e) are vortex beam phase distribution diagrams, respectively. Fig (f), (g), (h), (i), (j) are the light intensity distribution of the vortex beam, respectively. (a), (f) \( l=1 \); (b), (g) \( l=2 \); (c), (h) \( l=3 \); (d), (i) \( l=4 \); (e), (j) \( l=5 \).

3. Application of vortex beam on optical tweezers

Since Ashkin [12] published the first single-beam optical tweezers paper in 1986, the optical tweezers technology has been applied and developed in many fields after more than 30 years of development. We can achieve the movement of particles on the low-light level through optical tweezers. Non-contact operation can also greatly reduce mechanical damage. And precisely because of this feature, optical tweezers are widely used in the biological and medical fields. Particle manipulation. Optical
tweezers are highly focused by a laser beam as an excitation light source. The focused beam forms a potential well to capture and trap particles, also manipulates particles to achieve rotation [13]. However, it does not have perfect manipulation of all tiny particles, and there are still certain defects. Traditional optical tweezers technology uses the high focusing of ordinary Gaussian beams to capture particles [14]. The highly focused Gaussian beam has a large light intensity in the capture area of the particles, which will cause thermal damage to active objects such as cells, making the cells inactive, and Moreover, there is a problem of weak evanescent field, which is limited by the diffraction limit, resulting in a relatively weak gradient force, which will limit the capture efficiency of sub-wavelength size particles. Increasing the intensity of incident light will place high demands on the laser light source. And high-intensity laser power will limit the application and development of near-field optical tweezers. To solve this problem, people have developed surface plasmon optical tweezers technology, Surface plasmon optical tweezers technology has unique advantages in nanoparticle, metal particle capture, and near-field electromagnetic field enhancement and regulation, and has broad application prospects in the fields of bio sensing and surface enhanced Raman scattering. In 2001, Hiroshi Kano used Gaussian beams to excite surface plasmons [15], and compared and analyzed the intensity distribution of standing wave fields of SPPs excited in linear, radial, and angular polarization states. Previous studies on SPPs have mostly focused on the linear polarization of Gaussian beams, plane waves, and other focused laser beams. The intensity of SPPs irradiated by linearly polarized plane waves is weak, while the intensity of SPPs irradiated by linearly polarized Gaussian beams is higher than the former. The P. S. Tan research group obtained the SPPs field symmetrically distributed along the polarization direction through linearly polarized vortex beam induction [16], which shows that this excitation method is simple and feasible and suitable for studying SPPs interference of different metal dielectric structures. Ma Wenjuan et al. reported that the radially polarized vortex beams are all TM waves that excite SPPs on the metal surface, and obtained the SPPs interference field with a hollow annular distribution [17]. A. Bouhelier's group conducted experiments on vertically-induced SPPs induced by deep-focused Gaussian laser beams [18], and analyzed related characteristics. Although a Gaussian beam can excite SPPs, its central light intensity will interfere with the SPPs, thereby reducing the resolution of the interference fringes. In response to this problem, the vortex light field has a ring-shaped distribution of light intensity and the central optical axis intensity is approximately zero. The effect of the zero-order angle spectrum of the center of the Gaussian beam on the SPPs field can be eliminated, and the captured particles can be trapped in the light intensity. The center area of the beam is zero, so that the particle's activity is maintained, and the coverage area of the dark spot can be adjusted by changing the size of the topological charge to achieve precise control of the optical tweezers. Bazhenov first proposed that a hollow vortex beam can be used as a potential trap to capture cold atoms [19], and its corresponding "magneto-optical" trap structure has also been implemented in experiments. The zero dark light vortex can also become a physical instrument for generating light vortex tweezers. The use of vortex beams for optical capture can break through the traditional optical tweezers' requirements for the refractive index of particles, confine particles with a high refractive index near the focal point of the beam, and particles with a low refractive index will be confined to the focal plane above the focus.

In recent years, many researchers have done a lot of research on the deep focusing characteristics of various beams. Zhan studied the deep focusing characteristics of circularly polarized vortex beams and analysed the influence of related parameters on the focused beam distribution [20]. The results show that controlling the topological charge can control the size of the center and generate a focused spot with a concentrated light intensity. Moreover, the position of the focused spot can be controlled by rotating the incident light, which lays a solid foundation for the application of vortex beams to particle control. Hua analysed the tight focus characteristics of partially coherent vortex beams and proved that when the incident light is partially polarized or linearly polarized, an elliptical beam spot will be obtained [21]. Adjusting the parameters can also control the shape of the spot, which provides an theoretical basis for capturing elliptical particles. A study by Chen Ziyang's team at Huaqiao
University on deep-focused radial polarized vortex light in 2018\cite{22} proved the stable capture of gold particles and bubbles by this light source.

4. Conclusion
The uniqueness of the spatial phase of vortex beams has become a focus of current research and an important direction of frontier research. It has been widely used in many fields. Although the research on vortex beams in China started late, the application of optical tweezers has obtained fruitful results and made some progress. Further research on the characteristics of vortex beams will also expand our knowledge of physical optics, thereby promoting the application and development of vortex beams in optical information transmission, biomedicine and other aspects.

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