Coaxial multi-ring optical vortex generation based on compound spiral phase plates

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Abstract

We propose a new kind of compound optical vortex (COV) generator in this paper. The device consists of an inner spiral phase plate (SPP) and an outer annular spiral phase plate. There is an opaque band between two SPPs. Under the flat-top beam irradiation, concentric multi-ring COV rings with different topological charges in different radial radii can be generated. The theoretical analysis lays a theoretical foundation for the design of the COV generator, and the simulation results prove the effectiveness of the design. The unique characteristics of COV are discussed and some of its potential application scenarios are presented. This work provides a design method for generating COV using compound SPPs, and the advanced COV structure can help to expand the scope of utilization of vortex beam in optical tweezers, optical communication and other fields.

Keywords: optical vortex, spiral phase plate, singular optics

(Some figures may appear in colour only in the online journal)

1. Introduction

Since Coulet first proposed the concept of Light Vortex in 1989 [1], vortex beam has been rapidly developed and applied in various fields of scientific research and application. Vortex beam is a common form of optical vortex with phase factor \( \exp(i\ell \theta) \), where \( \theta \) is the azimuth angle and \( \ell \) is the topological charge [2]. Allen et al showed that each photon in such a beam carries an orbital angular momentum of size \( \ell \hbar \) [3].

Due to the unique characteristics of orbital angular momentum and zero light intensity in vortex center, vortex beams have great application potential. After years of development, vortex beam has been mainly used in optical tweezers [4–7], optical communication [8–11], quantum entanglement [12–14], imaging [15–18] and other aspects.

Here, a coaxial compound optical vortex (COV) is proposed, which consists of two or more optical vortices. The centers of multiple optical vortices are at the same point. Different types of compound vortex beams can be generated by adjusting the topological charge and ring spacing between two spiral phase plates (SPPs). We use different SPP to generate single optical vortex. The generating device of the COV is presented, and the characteristics of the light intensity distribution and phase distribution are introduced. The formation conditions and the characteristics of COV are discussed. We believe that the development of coaxial compound vortex beams will facilitate the development of complex particle control, high capacity optical communications, quantum communications, and optical sensing.
2. Simple optical vortex

Vortex beam is a kind of unique beam, different from the usual spherical light or plane light, vortex beam has a circular light intensity distribution, light intensity near the center of the vortex beam is zero. The phase of the vortex beam changes \(2\pi l\) uniformly around the center. \(l\) is topological charge, which is generally an integer. There are many methods to generate vortex beam, including cylindrical lens method [19, 20], holographic method [21, 22], spatial light modulator method [15], etc. The most efficient method to generate vortex beam is SPP method. The SPP is a kind of transmission optical element or reflective optical element whose thickness spirals up. The vortex beam generated by SPP is of good quality and easy to operate. The relationship between the thickness and the azimuth angle of the traditional transmission SPP can be expressed by the following equation:

\[
H = H_0 + H_1 \times \frac{\theta}{2\pi} \tag{1}
\]

where \(H\) is the phase plate thickness when the azimuth angle is \(\theta\), \(H_0\) is the base thickness of SPP, and \(H_1\) is the thickness difference between the thinnest and the thickest part of SPP. When the laser beam passes through the SPP, the phase delay generated can be expressed by the following equation:

\[
\varphi = 2\pi H \times \frac{n - n_0}{\lambda} \tag{2}
\]

From this equation, it can be concluded that when a beam of light passes through the SPP, the phase delay difference between the thinnest part and the thickest part is \(2\pi H_1 \times \frac{(n - n_0)}{\lambda}\), where \(H_1 \times \frac{(n - n_0)}{\lambda}\) can be expressed as \(l\), which is the topological charge.

Here we propose an annular spiral phase plate (ASPP) structure, the thickness of which can be expressed by the following formula:

\[
H = \left( H_0 + H_1 \times \frac{\theta}{2\pi} \right) \times \text{step}(r - r_2) \times \text{step}(r_3 - r) \tag{3}
\]

where \(r\) represents the radius, \(r_2\) represents the inner radius of the ASPP. It can be seen from the equation that this is an ASPP. The height at \(\theta\) is the same as that of a traditional SPP. Locations less than \(r_2\) are opaque. Both of the above two kinds of structures can generate a helical wavefront, so vortex beams with similar structure can be generated.

Figure 1(a) shows the structural schematic diagram of the SPP. Figure 1(b) shows the structural schematic of the ASPP. The radius of the inner ring is \(r_2\) and the radius of the outer ring is \(r_3\). Figure 1(c) shows the light intensity distribution and phase distribution of vortex beam generated when the SPP radius is 10 \(\mu\)m and the height difference is 3.8 \(\mu\)m. It is easy to see that the intensity of light produced by the traditional SPP is distributed as a bright ring, with the phase rotating counterclockwise and changing by thrice of \(2\pi\). This indicates that a three-order vortex beam is generated. Figure 1(d) gives the light intensity distribution of vortex beam generated on the image plane when the topological charge of SPP is 10 and the SPP radius is constant. As can be seen from the figure, compared with the vortex beam with topological
charge of 3, when $l = 10$, the spot radius of the vortex beam will increase. In the counterclockwise direction, the phase of the light changes 10 times of $2\pi$. Figure 1(e) shows the phase distribution and light intensity distribution on the image plane when the topological charge of ASPP is 3, $r_2 = 15 \mu m$, and $r_3 = 25 \mu m$. As can be seen from the figure, most of the light intensity of ASPP is distributed in the outer bright ring, but there is still some light intensity distribution in the inside of the bright ring. On the outside of the bright ring, the phase distribution is similar to the SPP, while near the center, several orders of light phases are entangled and form a vortex. As can be seen from figure 1(f), when the topological charge of ASPP increases to 10, only the phase changes, and the size of the vortices does not change significantly.

It needs to be pointed out that all the above results are based on Fresnel diffraction theory. Under the conditions of light wavelength of 632.8 nm, material refractive index of 1.5, we design a COV generator and use this model to verify its performance.

3. COV

In practical applications, we expect to generate a COV with two or more rings, and the topological charges in different radial regions is different. Therefore, the structure as shown in figure 2(a) was designed. There is a traditional SPP structure inside and an ASPP nested outside. The centers of the two SPPs are at the same point. Between the two SPPs is an opaque band. The inner SPP radius is $r_1$ and the topological charge takes $l_1$. The outer radius of the opaque ring is $r_2$. The outer radius of the outer ASPP is $r_3$ and the topological charge takes $l_2$. The maximum thickness difference in SPP and ASPP is $H_1$ and $H_2$. The vortex beam with different topological charges can be generated by changing $H_1$ and $H_2$ respectively.

Figure 2(b) shows the light intensity distribution and phase distribution generated by a COV generator. Under the circumstance of $r_1 = 10 \mu m$, $r_2 = 15 \mu m$, $r_3 = 25 \mu m$, $l_1 = 3$, $l_2 = 6$. As can be seen from the figure, a COV is generated. The inner vortex radius $R_1$ is 6.5 $\mu m$, and the outer vortex radius $R_2$ is 21 $\mu m$. There is obvious separation between the inner vortex and the outer vortex. It can be seen from the phase distribution that the phase of the inner vortex changes 3 times of $2\pi$, resulting in three order vortices. The phase of the outer vortex changes $12\pi$, resulting in six order vortices. Figure 2(c) shows the light intensity distribution and phase distribution when the topological charges of SPP and ASPP with opposite signs, and it can be seen that the inner and outer vortex radii of the COV do not change. The phase diagram shows that
because the topological charge of the inner vortex is negative, the rotation direction of the inner vortex changes clockwise. But it is still three order vortices. Similar to figure 2(b), phase distribution shows that there is no obvious separation between the inner and outer vortex. In figure 2(d), the size of $r_1$ and $r_3$ in figure 2(b) was changed from 10 $\mu$m and 25 $\mu$m to 20 $\mu$m and 45 $\mu$m, the width of opaque band remains the same. Light intensity distribution shows that the width of inner vortex and outer vortex increased obviously with the width increase of SPP and ASPP.

Through summary and analysis of sections 2 and 3, it can be concluded that the radius of vortex beam generated by SPP is mainly determined by two factors: the size of topological charge and the radius of SPP. In ASPP, things are different. In most cases, the radius of the ASPP is the only main factor that affects the vortex radius. The topological charge has little influence. However, when the topological charge of ASPP increases to a threshold, the size of the vortex will also increase with the increase of the topological charge. The main factors affecting the ring width in the light intensity distribution are SPP radius and ASPP ring width.

4. Discussion

When designing the COV generator, it is necessary to place the vortex with small topological charge in the inner ring as far as possible. This is because the topological charge $l$ has an obvious effect on the radius of vortex beam which is generated by SPP. The relation between the radius $R$ of vortex beam generated by SPP and the number of topological charges $l$ can be expressed by the following formula [23]:

$$R \approx a \frac{\lambda}{\text{NA}} \left(1 + \frac{l}{l_0}\right)$$

where $a$ and $l_0$ are constants related to the characteristics of the beam itself. NA is the numerical aperture, a constant related to the objective lens used in the optical path. $\lambda$ is the wavelength of light used to generate optical vortex. It can be easily seen from the formula that the radius of vortex beam is only related to the topological charge of vortex beam when it reaches a stable state. With the increase of $l$, the radius of vortex beam will also increase. Therefore, in the design of vortex generating device, the vortex beam with small topological charge should be placed in the inner ring as far as possible to avoid interference between internal and external vortices. However, it should be pointed out that it is possible to place vortices with large topological charge in the inner ring. Compared with SPP, the optical vortex generated by ASPP has a larger radius with the same topological charge. Therefore, within a certain range, the topological charge of the inner ring can be larger than that of the outer ring. The value depends on the width of the opaque band and the topological charges of optical vortices. As shown in figures 3(a) and (b), the COV generated by inner rings with different topological charges are shown. When $l_1 = 10$ and $l_2 = 6$, the inner and outer vortices remain distinct. When the topological charge of $l_1$ increases to 20, the inner vortex and outer vortex produce very obvious mutual interference.

Also note that the opaque band between the SPP and the ASPP is required in many cases. Although most of the energy of the vortex beam generated by SPP is concentrated in the main ring, there is still a certain distribution of light intensity outside. Therefore, the inner ring light and the outer ring
Figure 4. Light intensity distribution when $l_1 = 1$ and $l_2 = 3$ (a). There are two secondary peaks on both inner vortex and outer vortex. Phase of vortex beam with topological charges of 1 and 3 varies with azimuth angle (b). Radial represents the phase of the vortex beam, counterclockwise is the positive direction and represents the azimuth angle of the vortex beam. And two points of intersection can be seen in the diagram. Light intensity distribution when $l_1 = 1$ and $l_2 = -3$ (c). There are four secondary peaks on both inner vortex and outer vortex. Phase of vortex beam with topological charges of 1 and $-3$ varies with azimuth angle (d). Four points of intersection can be seen.

Light will inevitably produce some interference when the COV is generated. When the light of the inner ring is too close to the light of the outer ring, the degree of coherence will be too great to produce a clear separation between the inner and outer vortices. Figure 3(c) shows a vortex beam generated by COV generator which is removed opaque band and its results. It can be clearly seen that, compared with the results generated in figure 2(b), after removing the opaque band, due to the interference part of the light intensity superposition, three obvious connections are formed between two vortices. At the same time, the opaque band also cannot be transparent. As shown in figure 3(d), when the band becomes transparent, it will pass through the non-vortex beam field and interfere with the vortex beam field, which will affect the imaging quality of the vortex beam and lead to multiple high-intensity connection points between the inner and outer vortices. It is worth mentioning that in the case of a large difference between $l_1$ and $l_2$, an attempt can be made to remove the opaque band. Because the base difference between the inner and outer rings already provides enough distance. As shown in figure 3(e), $l_1 = 1$ and $l_2 = 20$, even if the opaque band is removed, a very clear inner and outer ring pattern is still generated. However, if the laser light intensity is too high, the nonlinear effect may occur due to the partial overlap of the inner and outer ring vortices at the early stage of propagation, thus affecting the quality of the distant vortices. So the feasibility of this idea still needs to be tested.

There is another noteworthy phenomenon in COV: there are secondary peaks in the inner and outer rings. And the number of secondary peaks can be expressed by the following formula:

$$N = |l_1 - l_2|$$

where $N$ is the number of secondary peaks and $l_1$ and $l_2$ are the topological charges. As shown in figure 4(a), when $l_1 = 1$ and $l_2 = 3$, two secondary peaks are generated on both the inner and outer vortices. As shown in figure 4(c), when $l_2$ changes to $-3$, the number of secondary peaks becomes four. The reasons for this phenomenon are as follows: although most of the intensity of vortex beam generated by SPP and ASPP is concentrated in a ring, there is a certain light intensity distribution outside the main ring. Although this kind of light intensity is weak compared with the main ring, the distribution of the light field still conforms to the law of vortex beam. Therefore, weak vortex beam with topological charge $l_1$ also exists on the main ring generated by ASPP. The constructive interference occurs at the position where the phase difference of
the two vortex beams is zero and the secondary peak is generated. At the same time, the trough occurs at the position of two vortex beams with opposite phase. Similarly, the weak vortex beam field of the outer ring vortex beam will also interfere with the main ring generated by SPP, and form the secondary peak which is equal the number of topological charge difference. Figure 4(b) shows the phase of vortex beam varies with azimuth angle in polar coordinates when $l_1 = 1$ and $l_2 = 3$. The radial direction of polar coordinates is the phase of vortex beam, and the positive direction is counterclockwise, representing the azimuth angle of vortex beam. It is easy to observe that when azimuth angle changes from 0 to $2\pi$, the phases of the two vortex beams intersect twice. When phase lines intersect, the phase difference of two vortex beams is zero, which means in these two points the constructive interference is the strongest. Similarly, figure 4(d) shows the light phase when the topological charges are 1 and $-3$. It can be clearly observed that there are four points of intersection, so there are four secondary peaks in the light intensity distribution. In order to reduce this phenomenon, an attempt can be made to widen the opaque band between the SPP and the ASPP, which will increase the distance between the two vortex beams, so as to reduce the influence of each other. At the same time, this phenomenon also has certain application value. Since the number of secondary peaks is related to the topological charges of the inner and outer vortices, the secondary peaks have the potential to be used in topological charge detection and verification for optical communication.

COV has unique advantages over single optical vortex in many fields. One of the main applications of optical vortex is manipulating microscopic particles. Each photon in optical vortex carries orbital angular momentum, so particles exposed to optical vortex are subjected to a force to the direction of rotation of the vortex. In this way, we can control the microfabricated machine. Since COV can produce optical vortices with different topological charges at different radii, different magnitudes and directions force can be generated at different positions by adjusting the size and symbol of the topological charge. This allows for more complex control of particle and microfabricated machines. Vortex beam is also widely used in optical communication. The capacity of optical communication is greatly increased by encoding the orbital angular momentum. Because COV can be generated by one beam of laser and can be adjusted for different orbital angular momentum at different radii. Therefore, COV has potential applications in the field of optical communication to further increase the capacity of optical communication.

In this work, we mainly carry out theoretical calculations and numerical simulations. In the actual manufacturing process, maskless lithography [24] or femtosecond 3D direct laser writing [25, 26] can be used. Grayscale lithography can be used to produce different doses of light at different locations in a photoresist plane of the same thickness, resulting in structures of different heights after development. Femtosecond 3D direct laser writing technology generates height difference on the material by different doses of irradiation in different exposure areas, and finally forms a COV generator.

5. Conclusions

We propose an ASPP structure different from the traditional SPP. By simulation, we verify the ability of ASPP to generate vortex beam when topological charges are 3 and 10 respectively. It is found that the topological charge of ASPP has little effect on the size of vortex. We also design a COV generator and use this model to verify its performance. The COV generator device was formed by combining ASPP with traditional SPP. Under the conditions of flat-top beam, appropriate thickness and suitable ring spacing, the COV generator can be applied to different wavelengths and generate COV with different topological charges combinations. Because of the positive correlation between the vortex radius and the topology charge, the vortex with small topological charge should be placed on the inside. When the difference of topological charges between two vortices is small, the vortices will interfere with each other. An opaque band could be added between the SPP and ASPP to improve the quality of the COV. The band should be as opaque as possible; otherwise, it will adversely affect the COV. When the difference of topological charges between inner and outer vortices is large, high quality COV can still be formed after removing the opaque band. The reason that secondary peaks occur both on the inner vortex and outer vortex is the interference between inner and outer vortices. Increasing the width of the opaque band can also reduce this phenomenon. There will be potential applications of COV in manipulating microfabricated machines and optical communication and so on.

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