Abruptly autofocusing polycyclic tornado ring Airy beam

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Abstract

We introduce numerically a new polycyclic tornado ring Airy beam (PTRAB) induced by annular spiral zone phases with the second order chirped factor. The PTRAB has such properties of controllable multi focuses, the multi optical bottles and rotation. By choosing appropriate parameters, we can control the times of the multi autofocus and the autofocusing distance, the size and the number of the OBs, the quantity of the spots and the location where the rotary direction changes from counterclockwise to clockwise. We believe our results have potential applications in laser energy focusing, optical tweezers, optical spanners and manufacturing tunable chiral meta-materials.

1. Introduction

Since the Airy beam was experimentally investigated [1], the self-accelerating Airy beam has drawn considerable attention. After decades, a large amount of the Airy beam distortion such as the ring Airy beam (RAB) [2, 3], the Airy vortex beam [4] and the symmetric Airy beam [5–7] were reported extensively. There was even a review article summarized the property of the Airy beam in 2019 [8]. Typically, the abruptly autofocusing (AAF) RAB can allow the intensity suddenly enhanced by orders of magnitude [2]. This AAF property is quite useful in laser biomedical treatment [2], optical trapping [9], multi-photo polymerization [10] and atom manipulation [11]. Besides, optical vortices (OVs) were also got a lot of attention because of the interesting property of the structuring light beam [12, 13]. OVs were characterized by a twisting wavefront, phase singularities and orbital angular momentum [14–17]. Those properties can be employed in many applications, such as optical communication [18], laser micro-machining [19, 20] and so on. Additionally, some in-depth researches also made OVs more complicated in different beams. The tight-focusing properties of a linearly polarized circular Airy Gaussian vortex beam with a high-numerical-aperture objective lens were outlined by Zhuang et al [21]. Brimis demonstrated that the Tornado waves were generated from the superposition of two RABs with the opposing helicity [22]. Also, the chiral structured beam was produced by the OVs [23]. In 2020, the generation of the tunable polycyclic chiral Gaussian beam by inducing annular spiral zone phases (ASZP) was numerically and experimentally derived [24].

Meanwhile, the effects of modulated vortex structures on different beams were also extensively studied. There were the sine modulated structure [25] and the cosine modulated structure [26] on the RAB. Moreover, the method dividing the element of the beam into a few sections to make each section have its own diffractive feature was also popular, such as the azimuthal-segmented linear zone plate [27], the Fresnel zone plate [28], bi-segment spiral zone plate [29] and multi-region spiral photon sieve [30]. It is expected that the chiral optical fields presented discriminatory effects with respecting to the OAM so that they can be employed in fabricating chiral micro-structure [31]. The spiral-shaped relief patterns were formed on an anisotropic polarization-dependent polymer by the focusing vortex beam [15]. Then, the chiral
nanoneedles opportune printed by a zero-OAM beam were shown by Syubaev et al [32]. Otherwise, the optical tweezers played an important role in the particle manipulation. It can be utilized on the applications of biology [33], soft condensed matter physics [34] and so on. Additionally, the optical bottle (OB) was a significant improvement on the optical tweezers. Since the OB beam was early proposed in 2000 [35], many researches concentrate on this new property which can allow the applications from trapping a single particle to multiple-particles [36]. The OB beam generates a dark region in the central part and offers an optical trap in three-dimension, so that it can be regarded as a kind of optical tweezers [36–40]. There are many methods to generate the OB beam, such as Fourier-space generation [41, 42] and caustics under revolution [43]. Especially, in reference [42], the huge OB from the RAB generated by Fourier-transforming chirped Bessel beams. In 2019, Zhang and her co-workers provided that a new kind of OB generated by using the principle of the second autofocusing of the chirped ring Pearcey Gaussian vortex beam [44].

Due to those special useful properties of the ring Airy Gaussian beam (RAGB) and the effects of the modulated phase, we set out to explore the RAGB with the ASZP. In this paper, we derive the AAF tunable polycyclic chiral RAGB which we define it as polycyclic tornado Airy beam (PTRAB). This new type of the RAGB shows the properties of multiple focuses, structured chiral vortex and rotation of the spot which is found numerous application in manufacturing tunable chiral meta-materials, forming the OBs to diversify the optical tweezers and optical communication. In section 2, we will derive the significant formula of the PTRAB and the method to generate the ASZP. Then, the controllable AAF ability, the multi OBs methods to generate the OBs to multiple-particles [36]. The OB beam generates a dark region in the central part and offers an optical trap in three-dimension, so that it can be regarded as a kind of optical tweezers [36–40]. There are many researches concentrate on this new property which can allow the applications from trapping a single particle to multiple-particles [36–50]. Finally, some useful conclusions will be summarized in section 6.

2. Theory

In the paraxial optical system with slowly varying envelope approximations, the optical wave $E$ of the PTRAB propagating in the free space can be described by the Huygens–Fresnel diffraction integral, which can be expressed in cylindrical coordinates [45]:

\[
E(r, \varphi, z) = \int_0^{2\pi} \int_0^\infty A_0 k \rho E(\rho, \varphi, 0) \exp \left[ ik \frac{r^2 + \rho^2 - 2\rho \cos(\varphi - \xi)}{2z} \right] d\rho \, d\xi, \tag{1}
\]

where, $A_0 = 1$ is the constant amplitude of the electric field, $r = \sqrt{x^2 + y^2}$ is the radial distance, $\varphi$ is an azimuth angle, $k = \frac{2\pi}{\lambda}$ is the wave number and $\lambda$ is the wavelength. The initial PTRAB can be expressed as:

\[
E(r, \varphi, 0) = A_0 Ai\left(\frac{r_0 - L}{bw_0}\right) \exp \left[a \left(\frac{r_0 - L}{bw_0}\right)\right] \exp \left[i\phi(r, \varphi)\right] \exp \left[-icr_0^2 \chi^2 \left(\frac{r_0 - r}{w_0}\right)^2\right], \tag{2}
\]

where, $w_0$ is the Gaussian waist, $r_0$ is the radius of the primary Airy ring, $Ai(\cdot)$ corresponds to the Airy function [46], $a = 0.1$ is the decaying parameter, $b = 0.2$ is the distribution parameter, $\chi = 1$ is a scaling factor of the Gaussian waist, $\kappa$ presents the second order chirped factor. Especially, such the ASZP $\Phi(r, \varphi)$ is formed by assembling multiple subphases, the phase distribution of the ASZP with the number $n$ (ASZP$n$) can be expressed as [24]:

\[
\Phi(r, \varphi) = \sum_{i=1}^{n} g_i(r, \varphi) \phi_i(r, \varphi). \tag{3}
\]

Here, $n$ is the number of the subphases (SPs) ($n = 1, 2, 3 \ldots$). $g_i(r, \varphi)$ denotes the corresponding transmittance and is written as [24]:

\[
g_i(r, \varphi) = \begin{cases} 1, & 0 < r < r_{\max} \\ 0, & \text{other} \end{cases} \tag{4}
\]

The $i$th subphase (SP$i$) can be expressed as [24, 47]:

\[
\phi_i(r, \varphi) = \begin{cases} \beta r_i, & r_{i,j} < r < r_{2,i} \\ \gamma, & r_{2,i} < r < r_{3,i} \\ l_{i\varphi} + \alpha r_i, & r_{3,i} < r < r_{4,i} \end{cases} \tag{5}
\]

here, $\beta r$, $\gamma$ and $l_{i\varphi} + \alpha r$ are the $i$th radial phase (RP$i$), the equiphase (EP$i$) and the spiral phase (SP$i$), respectively; $l_i$ presents the vortex topological charge for the SP$i$; $r_{1,i}$, $r_{2,i}$ and $r_{3,i}$ denote the inner radii of the RP$i$, the EP$i$ and the SP$i$, respectively; $r_{4,i}$ is the maximum radius of the $i$th ASZP and we set that
Figure 1. (a1)–(a3) Process for generating the ASZP \((n = 2)\) with \(\kappa = 37.28, n = 2, l_1 = l_2 = 6\) and \(\alpha = 2\pi;\) (b1)–(b3) process for generating the phase of the PTRAB; (c1) and (c2) normalized intensity distribution of the RAGB and the PTRAB.

\[ r_{\text{max}} = r_{k,i}. \]

Also, \(r_{2,i}, r_{3,i}\) and \(r_{4,i}\) are the outer radii of the RPi, the Epi and the SSPi, respectively. It is hard to solve the equation (1) combining with equations (2)–(5), however, we can use the split-step Fourier transform method to numerically simulate it fortunately [48]. In this paper, we assume that \(\lambda = 632\) nm, \(r_0 = 0.15\) mm, \(r_{1,1} = 0.1\) mm, \(w_0 = 1.5\) mm, \(\alpha = 2\pi, \beta = 0.5\pi\) and \(\gamma = 0\).

Figure 1 illustrates apparently the process for generating a complete phase of the PTRAB. In figure 1(a1), the SP has three parts. The ASZP with \(n = 2\) SPs (ASZP2) is the phase of the SP1 and the SP2 superimposed on each other as shown in figure 1(a3). Figure 1(b2) reveals the phase of the original RAB with the second order chirped factor. It merges with the ASZP2 and finally generates the phase of the PTRAB as seen in figure 1(b3). Moreover, from figures 1(c1) and (c2), we can learn that the intensity distribution of the PTRAB is similar to the RAGB [2]. In order to make it more obvious to show the size of each phase rings, we define the radii as:

\[
\begin{align*}
   r_{2,i} & = r_{1,i} + r_{\text{rp},i} \\
   r_{3,i} & = r_{2,i} + r_{\text{ep},i} \\
   r_{4,i} & = r_{3,i} + r_{\text{sp},i} \\
   r_{i,j+1} & = r_{i,j} + r_{k,i}
\end{align*}
\]

\(r_{\text{rp},i}, r_{\text{ep},i}\) and \(r_{\text{sp},i}\) are the rings length of the RPi, the Epi and the SSPi, respectively. For convenience, we define a matrix \(R_i = \begin{bmatrix} r_{\text{rp},i} & r_{\text{ep},i} \\ r_{\text{sp},i} & r_{k,i} \end{bmatrix}\) to describe them. In figure 1, the rings’ length is set as

\[ R_1 = R_2 = \begin{bmatrix} 0.2 & 0.2 \\ 0.25 & 0 \end{bmatrix} \text{ mm} \]

so the thickness of the SP1 and SP2’s rings is equal.

3. The abruptly autofocus and the radiation force of the PTRAB

The AAF property is a common feature of the RAGB [2, 49] and the ring Pearcey Gaussian beam [24, 50]. The physical reason of the AAF effect is the lateral acceleration of the Airy beams themselves. In this case, large transverse velocities are attained and energy rushes in an accelerated fashion toward the focus [2]. In reference [28], the principal focal point was displaced to the point that was supposed to be the focal length of a region that had a larger number of zones than the other. However, there is another definition for the abruptly autofocus. Therefore, we will state the AAF definition that while the maximum intensity of the AAF beam remains almost constant during propagation, it suddenly increases by orders of magnitude right before its focal point [2]. In this article, the abruptly autofocus of the PTRAB is multiple and controllable. Besides, we also utilize two kinds of the radiation forces which are the gradient force and the scattering force to describe the ability of optical trapping [51]. It is well known that the ability of optical trapping particles is related to whether the gradient force overwhelms the scattering force or not [52]. In this section, we will discuss the multiple AAF property and the radiation force of the PTRAB.

From figure 2, it is obvious that the intensity along the z-axis does not change with the vortex topological charges. From the previous researches [24, 27, 29, 30], the vortex topological charge \(l_i\) is included in the phase factor [equations (3) and (5)]. The parameters in \(\Phi(r, \varphi)\) do not directly affect the
maximum intensity value of PTRAB along z-axis. In addition, the phase modulation divides the element of the beam into a few sections so that each section has its diffractive feature. Therefore, the three curves are almost completely overlapping in figure 2(a). Intriguingly, there are three peaks when the number of the SP is \( n = 1 \). Among them, the first peak in figure 2 is relatively flat and the value is small, while the second peak marked with the black circle 2 is the highest surge, and the third peak marked with the circle 4 is relatively small but increases abruptly. Analyzing the curves carefully, we can find the surge points marked with two circles 1 and 3. Therefore, when \( n = 1 \), we consider that there are two abruptly focal points (AFPs) during the PTRAB propagation. Otherwise, the complex intensity profiles of the PTRAB at the two focal positions are outlined in figures 2(b1)–(b3) and (c1)–(c3). Although the maximum intensity of the PTRAB along z-axis in these three cases is the same, the intensity distribution is completely different. The number of side lobes has a very large relationship with the vortex topological charge \( l_1 \). Besides, while the \( l_1 \) increases, the overall spot will also become larger. We will discuss these phenomena in section 5 in detail.

Figure 3 describes that the PTRAB with different numbers of the SP will have different quantities of the AFPs. When \( n = 1 \), there will be two AFPs during propagation as shown by the red solid line in figure 3(a).
Figure 5. Propagation of the PTRAB in the free space with $w_0 = 1.5 \text{ mm}$, $l_1 = 6$, $\kappa = 37.28$, $n = 1$ and $R_1 = [0.2, 0.25, 0]$ mm; (a) side view of the PTRAB numerical propagation; (b1)–(b4) snapshots of the transverse intensity patterns of the PTRAB at planes 1–4 marked in figure (a); (c1)–(c4) the phase distribution.

The quantities of the AFPs will be three if the number of the SP is 2. Also, three peaks are relatively high, while the other one is the smallest. Similar to references [24, 39, 44], we can know that the second chirped factor will provide a focus. The quantities of the foci will be positively related to the number of the SPs. In addition, from figures 3(b1)–(b3), the intensity will decrease if $n$ increases. The pattern can be described that there is a high-intensity spot in the center and some low-intensity spots surround it. The pattern is like a ‘cogwheel’ or a ‘tornado’. That is the reason why we define the beam as PTRAB. With the increase of $n$, the surrounding spots will become more and more obvious, that is, the intensity of the surrounding spots will enhance relatively. Also, the larger number of the SPs is, the smaller intensity of the PTRAB in the free space is.

When the particle exists in a stable field, by using the vector identity and the solution of the Maxwell equations, the time-average gradient force and time-average scattering force can be expressed as [4, 53]:

$$F_{\text{grad}}(x, y, z) = \frac{2\pi \mu_0 n_2}{c} \frac{n_1^2 - n_2^2}{n_1^2 + 2n_2^2} \nabla I(x, y, z),$$ \hspace{1cm} (7)

$$F_{\text{scat}}(x, y, z) = \frac{8\pi k^4 \mu_0 n_2}{3c} \frac{n_1^2 - n_2^2}{n_1^2 + 2n_2^2} I(x, y, z) \hat{e}_z,$$ \hspace{1cm} (8)

where, $c$ is the light velocity, $\mu_0$ is the radius of the nanoparticle, $n_1$ is the refractive index of the particle, $n_2$ is the refractive index of the surrounding medium which is the free space ($n_2 = 1.00$), $n_1/n_2$ is the relative refractive index of a particle, $I(x, y, z) = cn_2 \varepsilon_0 \frac{|E(x, y, z)|^2}{2}$, $\varepsilon_0$ is the permittivity of vacuum. It is worth mentioning that the approximations of the radiation force which are outlined from equations (7) and (8) are on a dielectric sphere in the Rayleigh scattering regime and there exist different upper limits in a particle size between the longitudinal and transverse components of the radiation force [53]. In this paper, we assume that $n_1 = 1.33$.

In order to find the case where the gradient force is greater than the scattering force, we compare the magnitude of the two forces through different radii of the nanoparticle. From figure 4, while the situation is $\mu_0 = 3.08 \text{ nm}$, the two kinds of radiation forces are equal. When $\mu_0 < 3.08 \text{ nm}$, the gradient force begins to overwhelm the scattering force. That is, the ability of trapping particles becomes significant when the particle radius is less than 3.08 nm. However, the particles are so tiny that they are very sensitive to thermal fluctuations and Brownian motion. A necessary and sufficient condition for stable trapping is that the
potential well of the gradient force trap should be much larger than the kinetic energy of the Brownian particles [53]. The condition can be expressed as: \( \exp \left(-\frac{U}{k_B T}\right) \ll 1 \). Furthermore, it can be given in the present study [53, 54]:

\[
\frac{2n_2^2 \mu_0^3}{c^2 \left( \frac{n_1^2 - n_2^2}{n_1^2 + 2n_2^2} \right) \frac{2P}{u_0^2}} \geq 10k_B T, \tag{9}
\]

where, \( P \) is the beam power, \( k_B \) presents the Boltzmann constant and \( T \) denotes the temperature of the environment around the particle. Equation (9) provides the lower limit in particle size in the criterion. In our research, the smallest size of polystyrene spheres is \( \mu_0 = 180.35 \) nm, which is much larger than the ideal range. However, we can enlarge the beam power \( P \) of the PTRAB to decrease the lower limit of the trapping particle. When we increase the amplitude of the electric field \( A_0 \) to a certain level, we can achieve stable capture of particles. Simultaneously, this will only affect the magnitude of the radiation force and not the distribution. Therefore, in the rest sections of the paper, we can set the radius of the nano-particle as 3.00 nm and these side effects can be greatly reduced by increasing \( A_0 \).

We can summarize this section that the value of the vortex topological charge \( l_i \) does not affect the intensity during the propagation of the PTRAB. However, \( n \) has a great impact on the magnitude of the intensity and the quantities of the AFPs. As a result, the PTRAB can be used in the energy focusing, particle manipulation and controllable multi focuses. What is more, for the radiation force, the PTRAB will capture nanoparticles smaller than 3.08 nm more easily if the amplitude \( A_0 \) increased to a certain level.

### 4. The multi OBs formed by the PTRAB

References [8, 42] derived that the RAGB can form an OB in the free space. Different from it, the PTRAB can produce the multi OBs which are more helpful in the multi particles manipulation. One of the formation mechanisms of an OB is similar to the result in references [42, 44] which utilize the principle of the multiple focuses. According to the multiple autofocusing property in section 3, we outline a new kind of multi OBs generated by the PTRAB. In this section, we will further discuss the propagation path of the PTRAB. We will adjust the related coefficients to observe the size changing of the OBs.

First, we derive the typical simulation of single OB in figure 5. The OB is generated by the RAGB with the ASZP1. At the initial plane, we can find that the intensity distribution is quite similar to the RAGB and the phase is consistent with the properties which are demonstrated above. During propagation, the PTRAB first focuses at the plane 2 marked in figure 5(a). In addition, as can be seen from figures 5(b2) and (c2), its cross-section intensity distribution and phase are illustrated. Similar to figures 3(b1)–(b3), the main spot in the middle forms the head of the OB in figure 5(b2). Then, it diverges partially and forms the body of the OB as shown in figure 5(b3). At last, the beam focuses automatically again to form the bottom of the OB. The process of the OB’s generation is clearly derived according to figures 5(b2)–(b4). Besides, the change of the phase is demonstrated in figures 5(c1)–(c4). Interestingly, the spiral directions of the whole phase at the initial plane are clockwise, but the ASZP is counterclockwise as shown in figure 1(a1). Later in the process, the spiral direction of the intensity becomes counterclockwise in figure 5(b2). The rotary direction is decided by the direction of the ASZP. We will discuss this interesting phenomenon in detail in section 5.
Figure 7. Propagation of the PTRAB with different Gaussian waists and chirped factors in the free space; (a1) and (a2) peak intensity; (b1)–(b4) side views of the PTRAB numerical propagation. All the other parameters are the same as those in figure 5.

Figure 8. Propagation of the PTRAB with \( R_i = [0.20, 0.25, 0.25] \) mm and different numbers of the SPs in the free space; (a1) and (a2) side views of the PTRAB numerical propagation with \( n = 2 \) and \( n = 3 \), respectively; (b1)–(b10) snapshots of the transverse intensity patterns of the RTRAB at planes 1–10 marked in figures (a1) and (a2). All the other parameters are the same as those in figure 5.

Next, we can recognize the coincidence between the numerical simulation and the numerical experiment in figure 6. In numerical experiment, to interfere the plane wave with the PTRAB, the principle of holography is used [55]. In this way, we calculate the light field distribution of the interference between the plane wave and the PTRAB. Then, we select a positive first-order interference fringe on the spectrum plane and pass it through a lens, and the interference fringes of the interference beam at the image focal
plane of the lens are simulated by the computer. At last, in the real experiment, we can pass the fringe information \(6(b)\) to the spatial light modulator (SLM), and irradiate the SLM with light to produce the beam we want, the PTRAB. Figures 6(c1)–(c3) are the recorded intensity distributions of the PTRAB in numerical experiment. We prove that the OB can also be generated unmistakably by the PTRAB. The head, the body and the bottom are outlined in figures 6(c1)–(c3), respectively. The pattern is corresponding to that in figure 5.

Then, figure 7 demonstrates that the Gaussian waist can affect the distance between the two focal planes. From figures 7(b1) and (b2), the Gaussian waist is positively related to the distance between the focal planes. Figure 7(a1) outlines us the curves of the peak intensity and the distance between the focal planes of the PTRAB with different Gaussian waists while \(\kappa = 37.28\). Apparently, as the waist increases, both of the planes will move backwards and the distance between them will be longer. That is, \(w_0\) can adjust the length of the OB. On the other hand, the second order chirped factor also affects the distance between two focuses and the lengths of the OB. The opposite of the chirped factor is that \(\kappa\) is negatively related to the distance and the length of the OBs which is shown in figures 7(a2), (b3) and (b4). For these results, the length and the size of the OB can be controlled in two-dimension by adjusting the \(w_0\) and \(\kappa\). Also, both of them are positively related to the intensity of the PTRAB.

Next, figure 8(a1) demonstrates us the multi on-axis OBs generated by the PTRAB with the ASZP2. The intensity distributions at the planes 2 and 4 are the cross-sectional views of the bodies of the two OBs. According to the results in the section 3, the PTRAB with the ASZP2 has triple focuses and their positions are at the planes 1, 3 and 5. As a result, the two spaces between the three focal planes will form two small-scale OBs due to the partial divergence of the beam. When the ASZP changes from ASZP2 to ASZP3 that the side view is shown in figure 8(a2), the multi OB also exists. It is clear from figure 8(b7) that the central part is no longer a spot with none intensity but a small circular spot with larger intensity. Therefore, the OB at the plane 7 becomes like a bottle with a pillar in the middle. Besides, the size of the OB at the plane 9 is smaller than that at the plane 4. Also, there are some tiny OBs marked in the white oval on the left side and a relatively big OB on the right side of figure 8(a2).
Figure 10. (a1)–(a4) ASZP pattern with \( R_i = [0.2 \quad 0.2 \quad 0.25 \quad 0] \) mm; (b1)–(b4) snapshots of the transverse intensity patterns of the PTRAB at the position \( z = 150 \) mm; (c1)–(c4) phase distributions corresponding to figures (b1)–(b4); All the other parameters are same as those in figure 5.

At last, we can obtain that the magnitude of the gradient force is almost above that of the scattering force when \( \mu_0 = 3.00 \) nm from figure 9. It is obvious from figures 9(a1)–(a3) that there are many points where the combined force of the gradient force and the scattering force is zero. These trapping positions can provide the beam for a stably particle-trapping ability in the approximations. Moreover, figures 9(b) and (c) describe that the direction of the gradient force on the transverse section is to move closer to the trapping point. In the approximation of the radiation force, the scattering force in the longitudinal component does not play an essential role in resultant optical phenomena [53]. Therefore, we just use the gradient-force description in the transverse component to describe trapping ability. This proves that the OBs can trap nanoparticles and manipulate them. Besides, we can control the intensity of the PTRAB in disguise to control the magnitude of the radiation force.

To summarize this section, the multi OBs can be produced because of the multi focuses of the PTRAB. The length and the size of the OBs can be adjusted by changing the value of \( w_0 \) and \( \kappa \). Therefore, in the application of the optical tweezers, this new kind of beam can also have a great potential on the multi particles manipulation. However, there are some intriguing phenomena that the rotary direction of the spot and the phase will be different during the propagation. For example, taking figures 8(b), (b3) and (b5) as a group and figures 8(b6), (b8) and (b10) as another group, through comparing the figures in these two groups, the direction of rotation in figures 8(b1) and (b6) are counterclockwise while the directions in figures 8(b3), (b5), (b8) and (b10) are clockwise. Due to these interesting phenomena, section 5 springs up.

5. The OVs’ property of the PTRAB

In sections 3 and 4, both the spot and the phase rotation directions change during propagation. In this section, we will discuss the changes in spot and the phase to varying degrees in details.

From figures 2 and 10, we can know that the vortex stripes of the initial phase are related to the vortex topological charge. \( l_i \) reflects the number of the vortex stripes. There are 8 vortex stripes when \( l_i = 8 \), and 16 vortex stripes when \( l_i = 16 \) which is shown in figures 10(a1) and (a4). The spiral of the initial ASZP will not spin anticlockwise unless the vortex topological charge is positive integer. During the PTRAB propagating in the free space, the beam will be structured by the ASZP. The pattern becomes a tornado-like shape. Different from the reference [24], the surrounding spots are much weaker than the central spot. However, the phenomenon of the spot spiral is still relatively obvious in figures 10(b1) and (b2). When the two superimposed OVs are the opposite of each other, the spots spiralling around the center will become more scattered, but as a whole, it rotates counterclockwise like the patterns in figures 10(b1) and (b2).

Additionally, as the increase of the \( l_i \), the quantity of the spots surrounding the central spot also increases.
However, during the propagation, the direction of the spot’s rotation is not so simple as we have met above. We find that $z = 273$ mm is the position where the rotary direction of the spot changes if the $R_i$ remains the same. Before it, the rotation of the spots is counterclockwise which is marked by the white arrows as shown in figures 11(a1) and (c1). In figures 11(a2) and (c2), the rotation almost disappears although the clouds at the edge of the tornado (outer spots) spin counterclockwise slightly around the central part. After this position, the spots begin to rotate clockwise as shown in figures 11(a3) and (c3). In addition, when we concentrate on the phase in figures 11(b) and (d), it is apparent that the change mainly occurs in the middle. With the change of the propagation distance, there are many twisted rings caused by the phase advance or delay around the middle. When the direction is counterclockwise, the middle phase has a lap phase which is more advanced than that of the surrounding. Then, at the position where the rotation is almost stable, it evolves like a flower or a tornado. At last, it changes into the phase which is more delayed than that of the surrounding.

At last, the intensity patterns of the PTRAB with different rings’ length of the RP$i$, the Epi and the SSP$i$ are quite various. With increasing $r_{p,i}$, at the plane $z = 300$ mm, the intensity in the middle will be larger. From figures 12(a1)–(a3), we can also conclude that the surrounding spots get closer to the central spot. When $r_{p,i}$ increases, comparing to figures 12(a1)–(c1), the change in intensity is not very obvious, but the spiral spots are denser. With increasing $r_{p,i}$, the central intensity drops significantly and the surrounding intensity enhances as shown in figures 12(b1)–(b3). At last, it is clear from figures 12(c1)–(c3) that the larger $r_{k,i}$ is, the weaker the intensity is and the more scattered the surrounding spots are. More importantly, the rotary direction of the patterns in figures 12(a) and (c2) is almost non-rotating which means that we can adjust the distance of the direction change by changing these four values in the matrix $R_i$.

This section shows us the optical field can rotate continuously and automatically like the tornado. Moreover, the direction of rotation is not single. In our research, the plane of the direction change will appear near the plane $z = 0.3$ m. From reference [56], the digital micro-mirror can be assisted by the structuring tunable polycyclic chiral beams. In this case, we obtain the OBs generated by the PTRAB can
not only trap the multi nanoparticles but also can rotate the particles as the optical spanners. This brings more possibilities of facilitating this beam to rotary particles as optical spanners.

6. Conclusion

In summary, we present theoretically a new tunable polycyclic chiral beam generated by the RAB with the ASZP and the second order chirped factor which we define it as the PTRAB. Because the intensity and the phase distributions are similar to the tornado. After our in-depth research, we find that the multi focuses of the PTRAB is controllable. The vortex topological charge does not change the intensity of the PTRAB and the number of the SP during propagation. Meanwhile, when $\mu_0 < 3.08$ nm, the gradient force is larger than the scattering force, which means the nanoparticles can be trapped easily. Also, this kind of beam is also an OB beam which can form multi OBs in the free space. The Gaussian waist and the chirped factor can affect the distance between the two focuses so that it can adjust the length of the OBs. What’s more, the PTRAB with $n \geq 2$ can generate multi OBs. In part of the OBs, we also derive that the gradient force and the scattering force along x, y and z axes. It outlines the OB beam also fits the above situation. In the OVs’ part, the properties of the ASZP are shown apparently. The spots will vary with the changing of the topological charge $l_i$ and the matrix $R_i$. Importantly, the rotary direction of the spot will change near the plane $z = 300$ mm and the distance from the initial plane can be adjusted through changing the rings length of the ASZP. Based on the characteristics we have summarized above, we have confidence that such properties of the PTRAB can be utilized in the application of laser energy focusing, optical tweezers, optical spanners and manufacturing tunable chiral meta-materials.

Conflict of interest

We declare that we have no conflict of interest.
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