

## 基于特殊形貌光源的衍射效应对空心光场的调控研究

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**摘要** 在传统的轴棱锥-透镜光学系统中,产生局域空心光束的入射光一般为圆高斯光束。随着局域空心光束的系统多样化和应用多样化,研究具有特殊形貌的初始光束对局域空心光束的调控有重要的意义。圆高斯光束被多边光阑调制为特殊形貌的多边形光束,经过轴棱锥-透镜光学系统后产生局域空心光束。利用不同多边光阑,包括正三角形、正方形及正六边形,调控光学系统中的光场分布,并通过理论研究和实验测量得到光阑后的衍射光场变化。结果表明,利用多边光阑调控光场,产生的局域空心光束具有多个局部缺失部分。这些缺口的形成,对于多粒子捕获和精准捕获具有潜在的应用价值。同时,也对局域空心光束的多功能应用具有重要意义。

**关键词** 物理光学; 局域空心光束; 多边光阑; 光场调控

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### 1 引言

局域空心光束是一种沿光传播方向上有着强度为零的区域,而在此区域外的三维空间都围绕着高强度光的空心光束<sup>[1-2]</sup>,这种特殊的光束在诸多领域具有广泛应用<sup>[3-5]</sup>。由于局域空心光束具有三维封闭的暗中空区域,当粒子处于该空间时,受周围光的散射力作用,粒子不能逃出暗域,只能在某一位置处反复震荡,由此可以对微粒进行三维捕获及操纵,故局域空心光束在粒子操纵和微纳米技术方面有极高的应用价值<sup>[6]</sup>。以局域空心光束为捕获光束的光镊技术具有真正意义上的非接触、低损伤等优点,使操纵活体物质成为可能,在生物医学领域已有成功的应用<sup>[7]</sup>。

近年来,为了拓宽局域空心光束的应用范围,丰富局域空心光束的功能应用,对其进行光场调控和功能探索成为了众多科研人员研究的热点问题,其中利用多边光阑改变入射光源的特殊形貌是实现光场调控的有效手段之一<sup>[8-13]</sup>。2006年黄建国等<sup>[14]</sup>对均匀光条件下多边形光阑的菲涅耳衍射图进行了

详细的分析描述,并导出了衍射光场的简单表达式。2014年Nazari等<sup>[15]</sup>利用有限差分方法对一个亚波长多边形光阑的增强光传输及其偏振消光比进行了数值研究,分析并比较了多边形光阑(三角形、四边形、菱形、五边形光阑)系统中偏振对光传输的影响。2018年Shen等<sup>[16]</sup>利用激光谐振器产生了具有闭合多边形形貌的涡旋光束,即多边形涡旋光束。在多边形涡旋光束中,孤立点阵列分布在三角形、四边形和平行四边形路径上,其中光束的轮廓形貌可以通过调节腔长和泵浦点位置来控制。模拟和实验的结果验证了该方法的有效性,在粒子捕获和操纵等领域具有广阔的应用前景。2018年北京交通大学李润泉等<sup>[17]</sup>通过研究涡旋光经正六边形排列的多孔阵列衍射后的光强分布,分析了正六边形多孔阵列的结构参数对蜂窝状光场的影响,结果表明衍射光场会随着相位结构发生周期性变化,圆孔半径会影响衍射光场的范围,正六边形的边长对条纹的宽度和间距存在影响。局域空心光束作为光镊的捕获光束,对粒子的捕获和操纵有着巨大的优势,当多边光阑加入到其光学系统中对空心

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光场进行调控时,产生局域空心光束的功能性可以得到提升。

本文通过多边光阑(包括正三角形、正方形和正六边形光阑)获得多边形光束。由于光阑的孔径截断引起的衍射效应,入射光经轴棱锥-透镜系统之后分别形成了具有特殊性质和特殊形状的衍射光束和局域空心光束。通过对光学系统的理论分析和实验验证,研究不同的多边光阑对贝塞尔光束和局域空心光束的调控作用,并分析光场变化的规律。产生的局域空心光束具有多个局部缺失部分,这种具有多个缺口的局域空心光束有望扩大多粒子捕获及精准捕获的应用范围。

## 2 光学实验装置及理论分析

实验装置如图 1 所示,用变焦扩束器(5X-10X, Thorlabs, BE05-10-a)对 He-Ne 激光器(632.8 nm, LASOS-LGK7628)的入射光束进行了扩束。多边形的孔径光阑(正三角形、正方形和正六边形光阑)对入射光束进行调制,其中多边形的边长长度  $a = 6 \text{ mm}$ 。轴棱锥(Thorlabs, AX125-A)由折射率  $n = 1.47$  的熔融石英制成,底角  $\gamma = 5^\circ$ 。聚焦透镜(焦距  $f = 10 \text{ mm}$ , Thorlabs, AL1210-A)被放置在

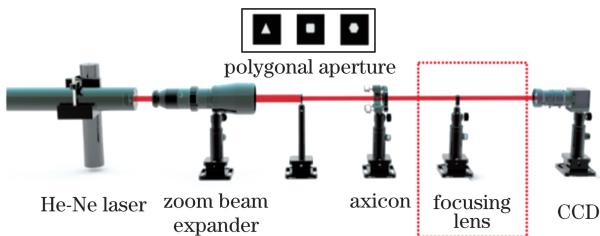


图 1 多边光阑的光学系统

Fig. 1 Optical system of polygonal apertures

轴棱锥后面。当研究光学系统中的贝塞尔光束时,实验装置需要去掉聚焦透镜。当研究光学系统中的局域空心光束时,实验装置需要放置聚焦透镜。用 CCD 摄像机(WP-HD200DS)检测光斑。

在通过多边光阑之前,激光光束只是被扩束而没有发生任何其他变化。高斯光束垂直入射多边光阑之前光场的表达式为

$$E_1(x, y) = E_0 \frac{w_0}{w(z)} \times \exp\left[-\frac{x^2 + y^2}{w^2(z)}\right], \quad (1)$$

$$w(z) = w_0 \times \sqrt{1 + \frac{z^2 \times \lambda^2}{\pi^2 \times w_0^4}}, \quad (2)$$

式中,  $w_0$  为激光光束的束腰半径,  $\lambda$  为入射光束的波长,  $E_0$  为光束的初始光振幅。为简单计算,假设  $E_0 = 1$ 。多边形的孔径光阑分为三种,不同光阑的透光孔径函数的表达式是不同的,即

$$T(x, y, 0) = \begin{cases} T_1(x, y, 0), & N = 3 \\ T_2(x, y, 0), & N = 4, \\ T_3(x, y, 0), & N = 6 \end{cases} \quad (3)$$

式中  $N$  为多边光阑的边数。其中光阑(正三角形、正方形、正六边形光阑)的透光孔径函数<sup>[17]</sup>表示为

$$T_{(1,2,3)}(x, y, 0) = \begin{cases} 1, & (x, y) \in R_{(1,2,3)} \\ 0, & \text{else} \end{cases}, \quad (4)$$

$$R_1 = \left\{ (x, y) \mid 3|x| + \sqrt{3}|y| \leq L, y \geq \frac{-L}{2\sqrt{3}} \right\},$$

$$R_2 = \{(x, y) \mid |x| \leq L/2, |y| \leq L/2\},$$

$$R_3 =$$

$$\{(x, y) \mid 3|x| + \sqrt{3}|y| \leq 3L, |y| \leq \sqrt{3}L/2\}.$$

因此,产生的多边形光束的表达式为

$$E_2(x, y) = E_1(x, y)T(x, y, 0). \quad (5)$$

通过轴棱锥之后的光场表达式为

$$E_3(x, y) = \frac{\exp(ikz)}{ikz} \exp\left[\frac{ik}{2z}(x^2 + y^2)\right] \iint_{0,0}^{r,r} E_2(x_0, y_0) \exp[-ik(n-1)\gamma r] \times \exp\left[\frac{ik}{2z}(x_0^2 + y_0^2)\right] \exp\left[\frac{2i\pi}{\lambda z}(xx_0 + yy_0)\right] dx_0 dy_0. \quad (6)$$

根据光学系统的理论分析和光场表达式,绘制了光路的示意图,如图 2(a) 所示。激光器出射的高斯光束被扩束后分别被不同边数的光阑调制,经过轴棱锥和透镜之后分别形成了对应特殊形貌的衍射光束,如图 2(b) 所示。与高斯光束经过轴棱锥形成的贝塞尔光束相比,多边形光束经过轴棱锥后,形成的衍射光束不再保持中心光斑

极强和传播过程中不发散的特性。由于光阑的孔径截断效应,衍射光束的中心能量出现多个部分的缺失,这种缺失部分的个数与多边光阑的边数恰好对应。多边光阑调控轴棱锥之后的衍射光束经过聚焦透镜后产生了携带有多个缺口的局域空心光束,因此多边光阑是影响局域空心光阱缺口的重要因素。

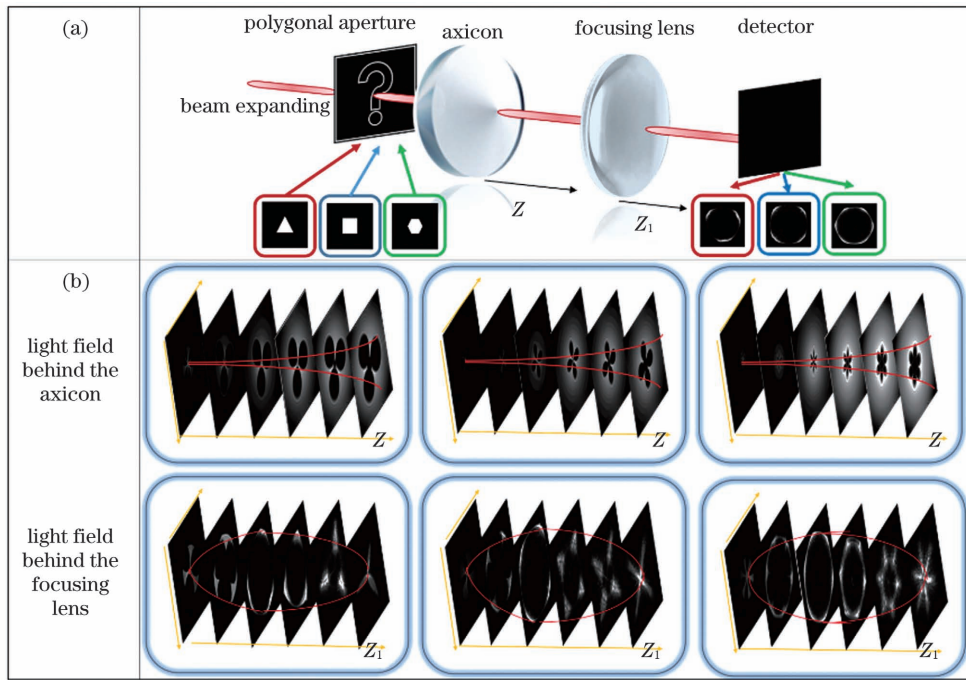


图 2 多边光阑调控光场的示意图。(a)系统结构;(b)多边光阑分别调控轴棱锥之后和透镜之后的光场

Fig. 2 Schematic diagrams of light field controlled by polygonal apertures. (a) System structure; (b) light field controlled by polygonal apertures behind the axicon and the focusing lens, respectively

### 3 数值模拟与实验结果

为了清晰地研究和观察光学系统中多边光阑的调控关系,通过理论分析和仿真模拟得到了多边形光束入射轴棱锥之后的光场分布。通过 Matlab 软件对(1)~(6)式进行数据解析,最终得到这种由特殊形貌的光束入射轴棱锥后衍射形成的光斑,如图 3 所示。

图 3 中分别展示了正三角形、正方形和正六边

形光阑的光场调控结果。在轴棱锥的光学系统中,由于多边光阑的调控作用,产生的无衍射光束已经发生了特殊变化。为了观察和分析光场的衍射现象,对光斑衍射图的位置坐标进行标记,以轴棱锥的中心为光学系统的坐标原点。当光阑为三角形光阑时,在轴棱锥之后 40 mm 处的内部中心为贝塞尔光斑,而外部形状为光强分布不均的三扇形。随着传输距离增加到 46 mm 处,中心的亮光斑开始发生能量分散和缺失。能量缺失部分的方位与三扇形的方

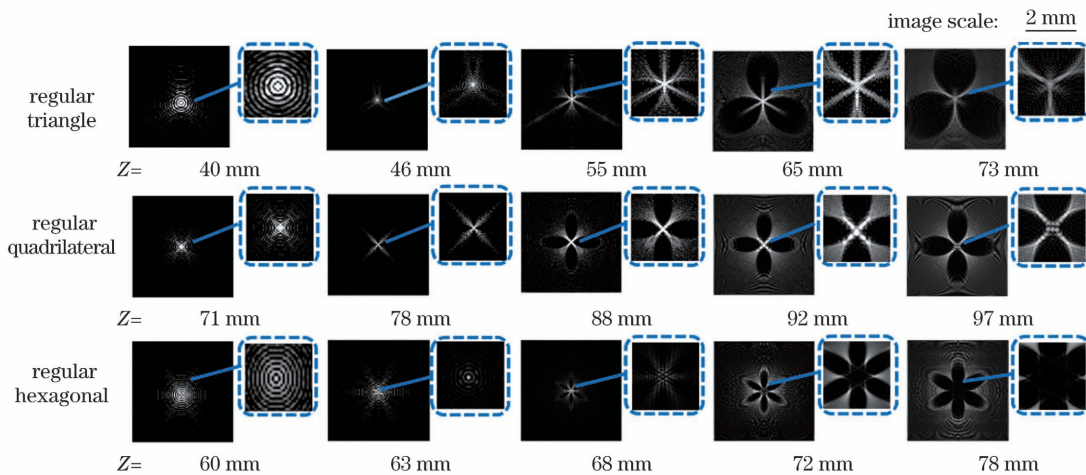


图 3 多边光阑调控光源经过轴棱锥之后的数值模拟光斑图

Fig. 3 Numerical simulation spot diagrams of the light source controlled by polygonal apertures after passing through the axicon

位一致。传输距离继续增加时,能量缺失的方位不变而缺失尺寸一直变大,直到 73 mm 处中心光斑完全消失。当光阑为正方形光阑时,在 71 mm 处内部中心为贝塞尔光斑,外部形状为四扇形。在 78 mm 的传输距离处光斑开始分散,能量的分散方位与四扇形的方位互补。衍射光束的传输距离增加的同时,光斑的中心处缺失尺寸也增大,直到在 97 mm 处中心光斑完全消失。当光阑为六边形光阑时,在 60 mm 处的衍射光斑类似于圆形的贝塞尔光斑,在 63 mm 处光斑开始分散,最终在 78 mm 处中心光斑完全消失。因此,通过奇数边的光阑和偶数边的光阑对光场的调控,在衍射传输距离方面和缺失能量的方

位方面是不同的,会产生与扇形的方位一致或者互补等两种情况。另外,随着光阑边数的增加,产生的衍射光斑逐渐趋向圆形光阑产生的衍射光斑。

为了验证理论数值模拟结果的准确性,我们同时搭建了如图 1 所示的实验装置,得到了多边形光阑入射轴棱锥之后的光场分布,如图 4 所示。我们把图 3 的模拟结果和图 4 的实验结果进行对比分析发现,衍射的光斑形貌和中心能量缺失的现象是一致的,理论模拟结果得到了验证。图 3 和图 4 中每张子图的中心区域都被局部放大,故根据光斑尺寸的变换关系,建立了子图光斑的比例尺 (image scale)。

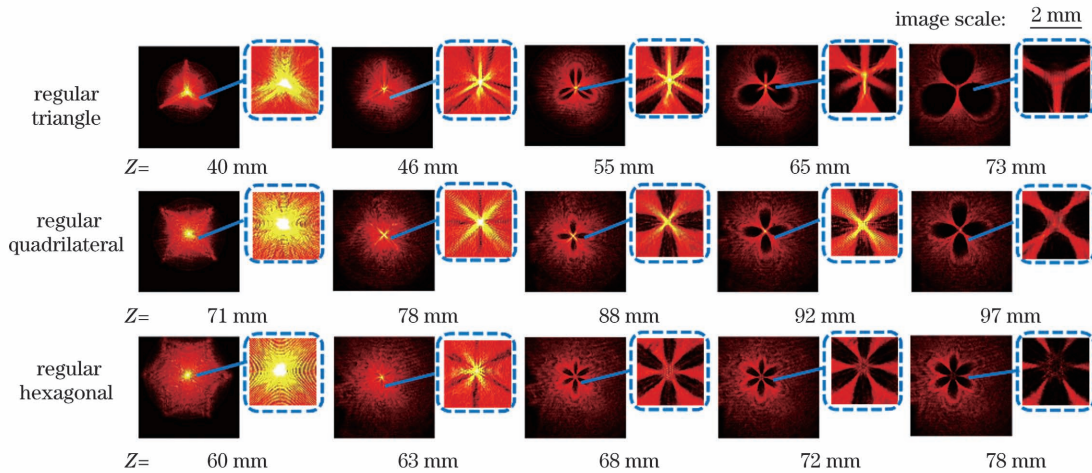


图 4 多边光阑调控光源经过轴棱锥之后的实验结果光斑图

Fig. 4 Experimental results spot diagram of the light source controlled by polygonal apertures after passing through the axicon

上述形成的特殊形貌的衍射光束经过聚焦透镜后,会形成带有缺口的局域空心光束。因此当研究局域空心光束的时候,需要在图 1 虚线框中放置聚焦透镜。根据轴棱锥之后的光场分布表达式 [(6)式]中的  $E_3(x_1, y_2)$ , 可得聚焦透镜之后的局域空心光场分布为

$$E_4(x, y) = \frac{\exp(ikz)}{ikz} \exp\left[\frac{ik}{2z}(x^2 + y^2)\right] \times \int_0^r \int_0^r E_3(x_1, y_1) \exp\left[-\frac{ik}{2f}(x^2 + y^2)\right] \times \exp\left[\frac{ik}{2z}(x_1^2 + y_1^2)\right] \times \exp\left[-\frac{2i\pi}{\lambda z}(xx_1 + yy_1)\right] dx_1 dy_1. \quad (7)$$

理论分析得知,特殊形貌的衍射光束被不同位置的聚焦透镜聚焦时,形成的光场分布是不同的。当聚焦透镜处的衍射光斑为贝塞尔光斑,即未发生能量分散时,产生的局域空心光束是完全闭合的,当

聚焦透镜处的衍射光斑已经发生能量分散时,产生的光束前焦点在聚焦透镜前面,而后焦点在聚焦透镜后面,不再是局域空心光束。因此为了保证局域空心光束能够正常形成,需要在衍射光束的中心能量即将分散且缺失的位置放置聚焦透镜,且需保证产生的局域空心光束不是完全闭合的以及两个焦点都在聚焦透镜的后面。根据图 3 和图 4 中光斑形状的位置所示,正三角形、正方形和正六边形光阑调控时,分别将聚焦透镜放置到 46, 78, 63 mm 处,得到如图 5 所示的局域空心光场。为了方便和清晰地观察局域空心光束,以聚焦透镜 ( $f = 10$  mm) 的中心为坐标原点。在 10 mm 处,光斑图像位于最大焦平面处。可以看出随着光束传播距离的增加,光斑中心处的能量开始出现分散并不断增大,在 10 mm 处中心能量分散达到最大,即暗域半径最大,之后暗域半径逐渐减小,整个过程中心光强由聚合到分散再到聚合,在聚焦透镜后形成一个携

带有缺口的局域空心光束。根据文中的聚焦透镜的焦距参数和轴棱锥的底角参数,利用文献[18]得出局域空心光束最大焦平面空心光斑的半径为 0.41 mm。由文献[19-20]可知,局域空心光斑的空心光斑尺寸在百微米量级时,比较适合捕获和操纵大尺寸的微粒。

从图 5 中可以看出局域空心光束的缺口位置和多边光阑是对应的,当多边光阑的边数为奇数时,局域空心光束的缺口位置与边位置互补,即与角位置相同,当多边光阑的边数为偶数时,局域空心光束的缺口位置与边位置相同,即与角位置互补。因此,我们可以根据光阑的奇偶边数定性分析产生的局域空心光束的缺口位置,这对于局域空心光束准确捕获

粒子具有重要的研究意义,可提高粒子的捕获效率。另外相对于圆高斯光束来说,多边光阑调控的特殊形貌光束可以形成携带有多个缺口的局域空心光束,这为多个粒子的同时捕获提供了可能性。

另外,研究发现,多边光阑的边数和局域空心光束的缺口数量是一致的,且随着多边光阑的边数增加,形成的局域空心光束的缺口尺寸逐渐减小。由于粒子的微小性,局域空心光束的缺口大小直接影响捕获粒子的受力情况,从而关系到粒子是否能够被稳定捕获,因此多边光阑可以调控形成不同尺寸缺口的局域空心光束,这对于不同尺寸粒子的捕获有着重要的研究意义,利于实现局域空心光束捕获微粒的多功能性。

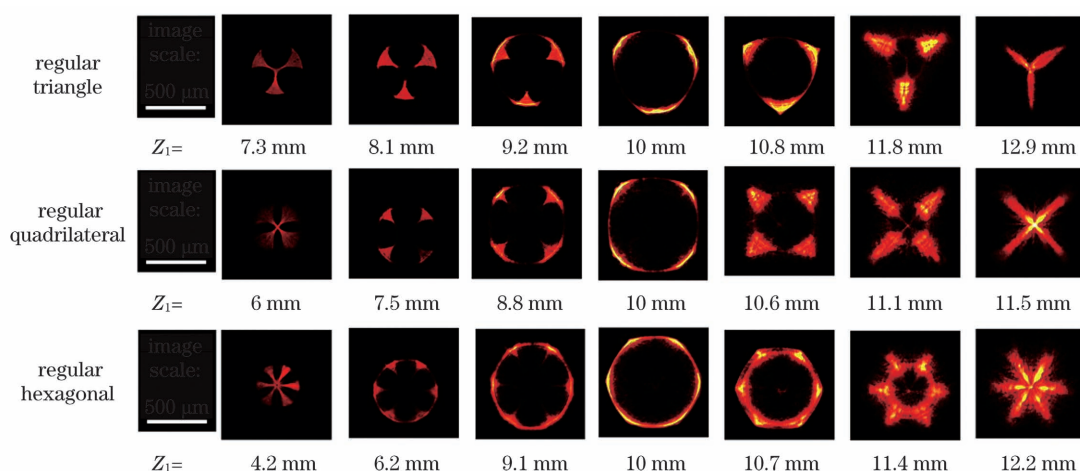


图 5 多边光阑调控光源经过轴棱锥和透镜之后的空心光斑图

Fig. 5 Hollow spot diagrams of the light source controlled by polygonal apertures after passing through the axicon and the lens

## 4 结 论

利用多边光阑(正三角形、正方形和正六边形光阑)对圆高斯光束进行调控,并对轴棱锥系统形成的衍射光束和局域空心光束进行了研究。研究的过程中,为了保证局域空心光束的产生,将聚焦透镜分别放置到 46, 78, 63 mm 处,形成的局域空心光束将携带有多个缺口。经过研究发现,形成的局域空心光束的缺口数量和缺口位置与多边光阑的边数是对应的。偶数边光阑产生的局域空心光束的缺口位置与边的位置相同,奇数边光阑产生的局域空心光束的缺口位置与边的位置互补,因此可以根据多边光阑的奇偶边数判断局域空心光束的缺口位置,进而提高精准捕获粒子的能力。同时可以根据光阑的边数来分析局域空心光束的缺口数量,实现多粒子捕获,提高捕获效率。另外分析得出局域空心光束的缺口

尺寸随着多边光阑边数数量的增加而减小。不同尺寸的局域空心光束的缺口是高质量捕获和稳定囚禁粒子的关键。

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# Modulation of Hollow Light Field by Diffraction Effect Based on Special Shape Light Source

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## Abstract

**Objective** Optical systems (OSs) that produce bottle beams (BBs) are increasingly diversifying in the literature, according to recent studies. However, the practicability of most OSs is relatively limited, and it has been difficult to meet the increasingly flexible application requirements. Therefore, under the premise of satisfying the properties of the bottle light field, it is necessary to design a controllable OS to obtain a multifunctional BB. In the traditional axicon-lens OS, the incident light that produces the BB is generally a circular Gaussian beam (GB). With the diversification of BB systems and applications, the initial beam with a special shape has important research significance for the regulation of BBs. Therefore, in this study, we design an OS for BBs and use the polygonal aperture to control the light field and analyze its characteristics. The circular GB was modulated by the polygonal aperture into a polygonal beam with a special shape. The BB produced after passing through the axicon-lens OS carries multiple notches. This has potential application value for multiparticle capture and precise capture and is of great significance for the multifunctional application of BBs.

**Methods** In this study, the axicon-lens structure was an OS, and polygonal apertures were placed before the axicon, so the BB with multiple notches was generated after the focusing lens. Polygonal apertures, including regular triangles, regular quadrilaterals, and regular hexagonal, were taken as the research objects. First, we theoretically analyzed and derived their transmission aperture functions, and used the Collins formula to calculate the light field distribution formula after the BB passes through the axicon-lens. Then, we used MATLAB software to analyze the theoretical formula and obtain the diffraction spot pattern after the axicon-lens via simulation and studied the relationship between the polygonal aperture shape and central diffraction spot. Finally, an experimental device of the OS was developed by replacing the polygonal aperture and using the charge-coupled device camera to observe the BB with multiple notches behind the focusing lens. Further, the influence of the number and position of the sides of the polygonal aperture on the notch of the bottle optical trap was studied.

**Results and Discussions** First, compared with the circular GB, the special shape beam could be adjusted by the polygonal aperture to form a BB with multiple notches (Fig. 2). The number of sides of the polygonal aperture was the same as that of the BB. In addition, the spot image obtained in the experiment showed that the notch position of the BB corresponded to the polygonal aperture. When the side number of the polygonal aperture was odd, the notch position of the BB was complementary to the side position, the angular position was the same. When the number of sides of the polygonal aperture was even, the notch position of the BB was the same as the side position, complementary to the angular position. Therefore, we could qualitatively analyze the notch position of the BB generated according to the odd and even number of apertures (Fig. 5). Finally, we found that as the number of sides of the polygonal aperture increased, the notch size of the BB gradually decreased. It has important research significance of the capture of particles with different sizes.

**Conclusions** A circular GB was regulated by the polygonal aperture (regular triangle, regular quadrilateral, and regular hexagon), and the diffracted beam and BB formed by the axicon system were studied. In the research process, to ensure the generation of the BB, the focusing lens was placed at 46, 78, and 63 mm, respectively, and the formed BBs carried multiple notches. After the research, we found that the number of the notches of the formed BBs corresponded to the number of sides of the polygonal aperture. The notch position of the BB generated by the

even-numbered side aperture was the same as the position of the side, whereas that of the BB generated by the odd-numbered side aperture was complementary to the position of the side, and the local area could be analyzed according to the number of sides of the aperture. In addition, the analysis showed that the notch size of the BBs decreased with the increase in the number of sides of the polygonal aperture. The notch of the BB of different sizes was the key to high-quality capture and stable trapped particles. The radius of the largest focal plane hollow spot of the BB was 0.41 mm. The hollow spot size of the bottle optical trap was in the order of hundreds of microns, which was more suitable for capturing and manipulating large-sized particles.

**Key words** physical optics; bottle beam; polygonal aperture; light field control

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