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Generating Composite Vortex Beams with Single-Helicity Annulus-Sector Spiral Zone Plates

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Abstract

Composite vortex beams (CVBs) with multiple spatial singularities and orbital angular momentum (OAM) are widely used in various applications including multiple optical traps and optical communication. Here, based on the equal-angle segmentation and radial displacement modulation approach, we propose an innovative scheme for generating CVBs with controllable OAM spectrum by proposing a simple and compact optical element termed as single-helicity annulus-sector spiral zone plates (SASZPs). Theoretical analysis reveals that by modulating the structural parameters of the SASZPs, such as the topological charge, the radial misalignment parameter and the number of annulus-sector primitives, an attractive intensity pattern consisting of petal-like structures can not only be produced but also the mode purity of CVBs can also be flexibly controlled. In addition, by adopting the high-quality and low-defect diamond substrate we have synthesized, based on the electron beam lithography technology and dry etching technology, the SASZP samples with different parameters have been fabricated and the focusing properties of such optics in the visible light region have been carried out and verified. These findings direct a new avenue for improving the performance of ultra-compact solar-blind UV imaging, optical communication and integrated optics.

Keywords: composite vortex beams; orbital angular momentum; spiral zone plates

1. Introduction

In recent years, the generation, control, and application of vortex light have gradually become key topics of discussion [1–4]. Optical vortex refers to a special structured light field with an annular intensity distribution and a helical phase structure, which carries the new degree of freedom in orbital angular momentum (OAM) [5–7]. Specifically, the vortex beams with the OAM are a new and ideal tool for selectively exciting dipole-forbidden states by linear optical absorption [8]. In addition, due to OAM properties of vortex beams, it has also been widely applied in many fields, including optical communications [9,10], particle manipulation [11–13], multi-band diffraction [14] optical microscopy [15,16]. Over the past few decades, researchers have successively proposed a series of methods that can generate vortex beams in practice, such as Spatial Light Modulators (SLMs) [17], spiral phase plates (SPPs) [18–20], metasurface [21–23], Devil's vortex lenses [24], and spiral



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pinhole plates [25]. However, most of these methods are primarily used to generate vortex beams with a single mode, whereas the OAM-based applications are not limited to a single mode on some occasions.

Nevertheless, different from the single mode as that of the conventional optical vortex, CVBs have been extensively adopted in the fields of optical encryption [26], optical manipulation, optical tweezers [27] high-dimensional information encoding, and quantum communication considering the unique multi-modal OAM properties. Typically, in the field of particle manipulation, CVBs enable more intricate particle control by virtue of their multiple OAM modes [28,29]. In the field of optical information encoding, by superimposing multiple OAM modes in the beam and combining other degrees of freedom such as polarization degree of freedom and spatial mode degree of freedom, the dimension and capacity of information encoding have been greatly expanded [30]. In addition, due to the special phase distribution of CVBs, it can be used to create super-resolution imaging systems beyond the diffraction limit [31]. Moreover, by enhancing the data transmission efficiency and capacity of free-space optical communication systems, CVBs have also exhibited attractive applications in the field of optical communication [32,33]. Especially, apart from the property of carrying multiple OAM modes, for CVBs with high-purity OAM modes have been endowed as an extensive alternative in free-space optical communication systems and fiber-optic communication as they are not only less likely to couple with other modes and to do so effectively to reduce the inter-channel crosstalk, but they can also improve system robustness [34,35].

According to the discussion above, the generation and application of CVBs have nowadays become a hot topic in the field of optics. As a representative, CVBs can be produced based on interferometric techniques by linearly superposing two or more LG beams with distinct topological charges together [36–38]. Meanwhile, the SLM which can flexibly construct and manipulate complex optical field structures with its precise phase modulation capability has been widely applied to produce CVBs. For instance, a methodology which is simple, flexible, perfectly aligned beams and insensitive to mechanical vibrations has been investigated to generate CVBs with high symmetry by independent Spatial Light Modulator pixel addressing [39]. However, this scheme still suffers from the unavoidable large volume, high cost, and low resolution. In comparison, considering the advantages in terms of flexible wavefront manipulation, low cost, simplified and compact experimental setups, diffractive optical elements (DOEs) such as modulated helicon–conical phases [40], geometric metasurface [41,42], and fork gratings [43] have served as important approaches for CVBs generation. Particularly, an interesting scheme for generating CVBs termed Azimuthal Phase-shifted Zone Plates (APZPs) have been proposed to generate CVBs with petal-like beams by superposing masks with opposite helicity together [44]. Regardless, these typical techniques need to sacrifice continuous phase degree of freedom and in this process unnecessary high-order diffraction noise will be introduced. Consequently, the purity of the OAM mode will unavoidably be reduced.

In this investigation, we have proposed an effective and straightforward methodology for producing CVBs with controllable OAM spectrum which are termed SASZPs. By combining the equal-angle segmentation and radial displacement modulation approach together, we have modulated the transparent and opaque zones of the conventional spiral zone plates and the attractive focusing intensity distributions with petal-like structures in the propagation direction can thus be obtained. In addition, by controlling the optical parameters of such optics as the topological charge, the radial misalignment parameter and the number of annulus-sector primitives, the composition of the OAM modes can be flexibly controlled. Compared with the conventional CVBs generation methodology, our proposal can be widely used in various applications considering the advantages of single-

piece miniaturization, harsh environmental stability, low diffraction noise, easy fabrication, and broadband compatibility. Particularly, the CVBs produced by SASZPs can improve the security of physical-layer communications, effectively suppress the offset side lobes generated, expand the dimension and capacity of information encoding and reduce the inter-channel crosstalk but can also improve system robustness, which enable they can be an attractive alternative for the fields of optical communications [45], superoscillation [46], quasilattice vortex fields [47] and vector-field mapping [48]. Specifically, compared with the fused quartz or metals, considering the excellent characteristics of the diamond in terms of wide band gap, high thermal conductivity, high radiation resistance, high transmissivity, high thermal conductivity and low thermal expansion coefficient, they can be widely used in optics fields such as solar-blind ultraviolet imaging [49,50], metasurface for information encryption [51], photodetector [52], and X-Ray Free-Electron Laser [53]. Especially considering diamonds have a low coefficient of thermal expansion, the diamond substrate diffractive optical elements can exhibit superior and stable focusing characteristics even under harsh conditions such as high temperature and high pressure. To verify the above theoretical conjecture, we have first synthesized high-quality single-crystal diamond by using the Microwave Plasma Chemical Vapor Deposition (MPCVD) and subsequently fabricated the diamond-based SASZPs samples with different parameters based on the electron beam lithography technology and dry etching technology. To verify the focusing properties of the SASZPs, we have also carried out the demonstrated experiment, which accords well with our physical design and anticipation. These findings provide attractive alternatives in the fields of EUV solar telescope, holographic imaging and nanoprobe.

2. Design and Method

As shown in Figure 1a we start our physical design from equally dividing the conventional spiral zone plates (SZPs) into N annulus-sector primitives along the azimuthal direction, where N denotes the number of annulus-sector primitives in per zone and each angle is $2\pi/N$.

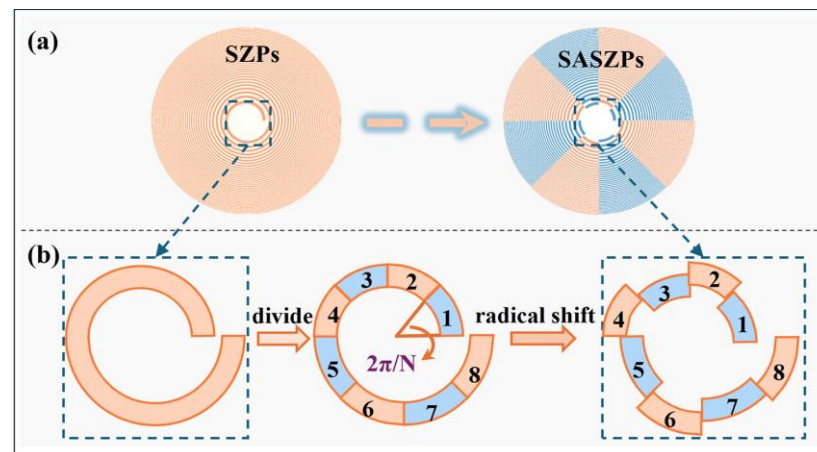


Figure 1. (a) The schematic of SZPs with $l = 1$, and the schematic of SASZPs with $l = 1$, $N = 8$, $h = 1$; (b) design of the transformation diagram from SZPs to SASZPs.

Specifically, for conventional SZPs, from the Fresnel diffraction integral [54], we have that the central position of the m th zone is given by:

$$R_{center}(r, \theta) = \sqrt{\frac{\lambda f}{\pi} (l\theta + \pi/2 + 2m\pi)} \quad (1)$$

where (r, θ) is the polar coordinate, $\pi/2$ is the initial angular offset of the SZPs, which is used to control the starting position of the SZPs and the azimuth angle, and l and θ represent the topological charge, respectively. Furthermore, the λ and f are denoted as wavelength and focal length of SZPs, respectively. Let $\theta' = l\theta + \pi/2$, the corresponding width of m th zone D_m can be calculated by the difference in the central positions of adjacent zone where the m th zone located, meaning that $D_m = R_{center}(m) - R_{center}(m-1)$, after substituting it into Equation (1) and performing an exact calculation, we can obtain that the D_m can be expressed as:

$$D_m = \frac{\sqrt{\lambda f \pi}}{\sqrt{(2m+1)\pi + \theta'} + \sqrt{2m\pi + \theta'}} \quad (2)$$

Meanwhile, the annulus-sector primitive in the different zones have different radial widths and gradually decreases with radius increase. Based on this, we introduce a radial displacement function (H_{rsf}) to control the radial displacement of annulus-sector-shaped primitives, and H_{rsf} can then be represented as follows:

$$H_{rsf} = h \cos[(n_m - 1)\pi] \quad (3)$$

where h is the radial misalignment parameter, and the range of its value varies from 0 to 1. Typically, it should be noted that as the value of $h = 0$, it corresponds to the conventional SZPs. The parameter n_m represents the n th sector on the m th zone, n is the ordinal number of the sector ($n \leq N$). This design leverages the property that the extrema of the cosine function have opposite signs, equal magnitudes and vary periodically with the angle, thereby enabling the cyclic modulation of the radial displacement of the annulus-sector primitives in the zone.

It is worth noting that the value of N must be even to ensure opposite radial displacements between adjacent primitives in our design. Therefore, the inner radius of the m th zone is $R_{im} = R_{center} + D_m(H_{rsf} - 1)/2$ and the outer radius is $R_{om} = R_{center} + D_m(H_{rsf} + 1)/2$. The transmittance function of the SASZPs in the polar coordinates is expressed as:

$$t(r, \theta) = \sum_m \text{sign}[(r - R_{im}) \& (R_{om} - r)] \quad (4)$$

When the proposed SASZPs is illuminated by monochromatic plane waves with an incident wavelength of λ , the intensity distribution at a distance z from the diffraction plane can be written as Equation (5):

$$I(\vec{\rho}, z) = \left| \frac{\exp(ikz)}{i\lambda z} \iint t(r, \theta) \exp\left[\frac{ik}{2z}(|\vec{\gamma} - \vec{\rho}|^2)\right] d\vec{\gamma} \right|^2 \quad (5)$$

where $\vec{\rho}$ and $\vec{\gamma}$ are the coordinates of observation and diffraction plane, respectively.

3. Result

To validate the influence of the structural parameters such as the radial misalignment parameter h , the topological charge l and the number of annulus-sector primitives N on the intensity distribution of the focused optical field of the SASZPs, based on the Fresnel–Kirchhoff diffraction theory and convolution theorem, we have numerically simulated the focused properties using the control variable method. In the simulation, the wavelength λ of the incident light is 532 nm, the focal length f is 245 μm and the number of zones in SASZPs is 37, respectively. Firstly, we investigate the focusing properties of the SASZPs as the radial misalignment parameter h is varied from 0 to 1 with an incremental step of 0.25.

Meanwhile, the topological charge and the number of annulus-sector primitives remain changeable, which are chosen to be $l = 2$, $N = 8$, respectively. It can be concluded from Figure 2a that as the radial misalignment parameter h increases from 0 to 0.5, the original circular light intensity pattern transforms into four symmetrical bright spots arranged in a cross shape. Then as the radial misalignment parameter h gradually increases from 0.5 to 1, the original four bright spots gradually merged and evolved into eight bright spots; the evolution process is shown in Figure 2b. Secondary diffraction begins to appear around the bright spots, and thus a composite circular pattern with secondary diffraction was eventually formed.

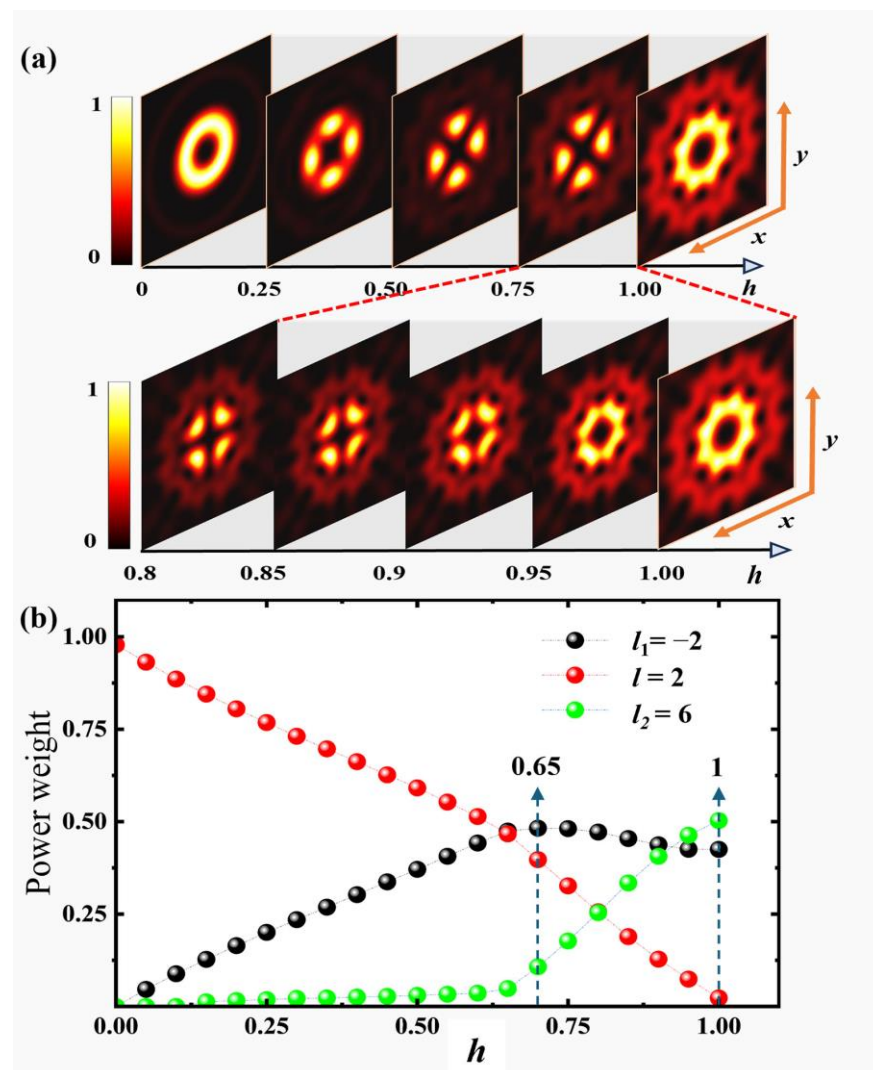


Figure 2. (a) Simulated intensity profiles at the focal plane of SASZPs with different values of h ($l = 2$, $N = 8$) and the evolutionary process of the number of petals in CVBs changing from 4 to 8 when h changes from 0.75 to 1; (b) evolution of OAM modes and their mode purity of the diffracted beam at the focus with h .

Simultaneously, when the vortex light field passes through the periodic structure modulation, due to the angular modulation coupling effect of the rotationally symmetric structure, the initial OAM main mode will undergo mode splitting. Thus, the split OAM spectrum will mainly consist of the original mode topological charge $l = 2$ and the symmetrical side lobes $l_1 = l - N/2$ and $l_2 = l + N/2$ on both sides, respectively. Here, in our physical design, as the topological charge of the SASZPs and the number of annulus-sector primitives are chosen as the topological charge $l = 2$ and the number of annulus-sector

primitives $N = 8$, then after periodic modulation, the typical OAM spectrum distribution with the characteristic of three peaks which consist of the central main peak $l = 2$, the left side lobe $l = -2$, and the right side lobe $l = 6$ will be formed.

In addition, based on the OAM spectrum decomposition theory, we can know that the complex amplitude $u(r, \varphi)$ of an arbitrary optical field can be expanded into a series of spiral harmonic basis functions $\exp(il\varphi)$ [55,56], which can be expressed as:

$$u(r, \varphi) = \frac{1}{\sqrt{2\pi}} \sum_{l=-\infty}^{\infty} \alpha_l(r) \exp(-il\varphi) \quad (6)$$

where the weighting coefficients $\alpha_l(r)$ that can be computed as:

$$\alpha_l(r) = \frac{1}{2\pi} \int_0^{2\pi} u(r, \varphi) \exp(il\varphi) d\varphi \quad (7)$$

Consequently, for different values of the radial misalignment parameter h , we can calculate the proportion of each OAM mode of specific topological mode.

Based on the discussion above, we can conclude from Figure 2b that as the values of the radial misalignment parameter h increase, the proportion of the initial mode $l = 2$ steadily decreases and eventually approaches zero. Meanwhile the left lobe l_1 gradually increases as the values of the radial misalignment parameter h increase and eventually remain nearly stable. However, although the proportion of the right lobe l_2 initially is very small, the value gradually increases with the values of the radial misalignment parameter h increases. It should be noticed that as the value of the radial misalignment parameter h equals 0.65, the OAM spectrum consists mainly of two modes, l_1 and l , which preserve the equal proportion with nearly 50%. At the same time, the rest of OAM mode l_2 can be almost ignored. For another specific case, as the radial misalignment parameter h increases to 1, the OAM mode l decreases to zero and the OAM spectrum distribution can be approximately regarded as a superposition state of l_2 . It is known to us that in practical applications, CVBs with high OAM mode purity l_1 have more advantages in the field of optical communication. As a representation, to further investigate the influence of the structural parameters' topological charge l and the number of annulus-sector primitives N the OAM spectrum, we selected the specific case of $h = 1$ which superimposed two OAM modes as the focus of subsequent studies to generate CVBs with controllable mode purity.

Subsequently, to further discuss the influence of the number of annulus-sector primitives N on the focusing property of the SASZPs, here we keep the values of the radial misalignment parameter $h = 1$ and the topological charge $l = 2$ unchanged while the number of annulus-sector primitives N are chosen as 6, 8, 10, respectively. As displayed in Figure 3(a1–a3), after the incident light modulated by the SASZPs, CVBs with a petal-like intensity distribution and center zero light intensity are generated at the focal plane. Moreover, it can be clearly seen that as the values of the number of annulus-sector primitives N increase, the number of bright petal-like spots in the peripheral are not only correspondingly increased but also preserve the same values with that of the number of annulus-sector primitives N . In addition, from the calculation as presented in Figure 3(b1) we can obtain that as the topological charge $l = 2$ and the number of annulus-sector primitives $N = 6$, the exhibiting OAM mode spectrum is the overlap of two modes which are $l_1 = 4$ and $l_2 = -2$ and the difference is N . In addition, the calculations illustrated in Figure 3(b2,b3) both follow the same trend as in Figure 3(b1), which accord well with the orbital angular momentum spectrum decomposition theory as described in Equations (6) and (7). According to our analysis, we can conclude that the number of bright petal-like spots in CVBs can be flexibly controlled by adjusting the value of the number of annulus-sector primitives N .

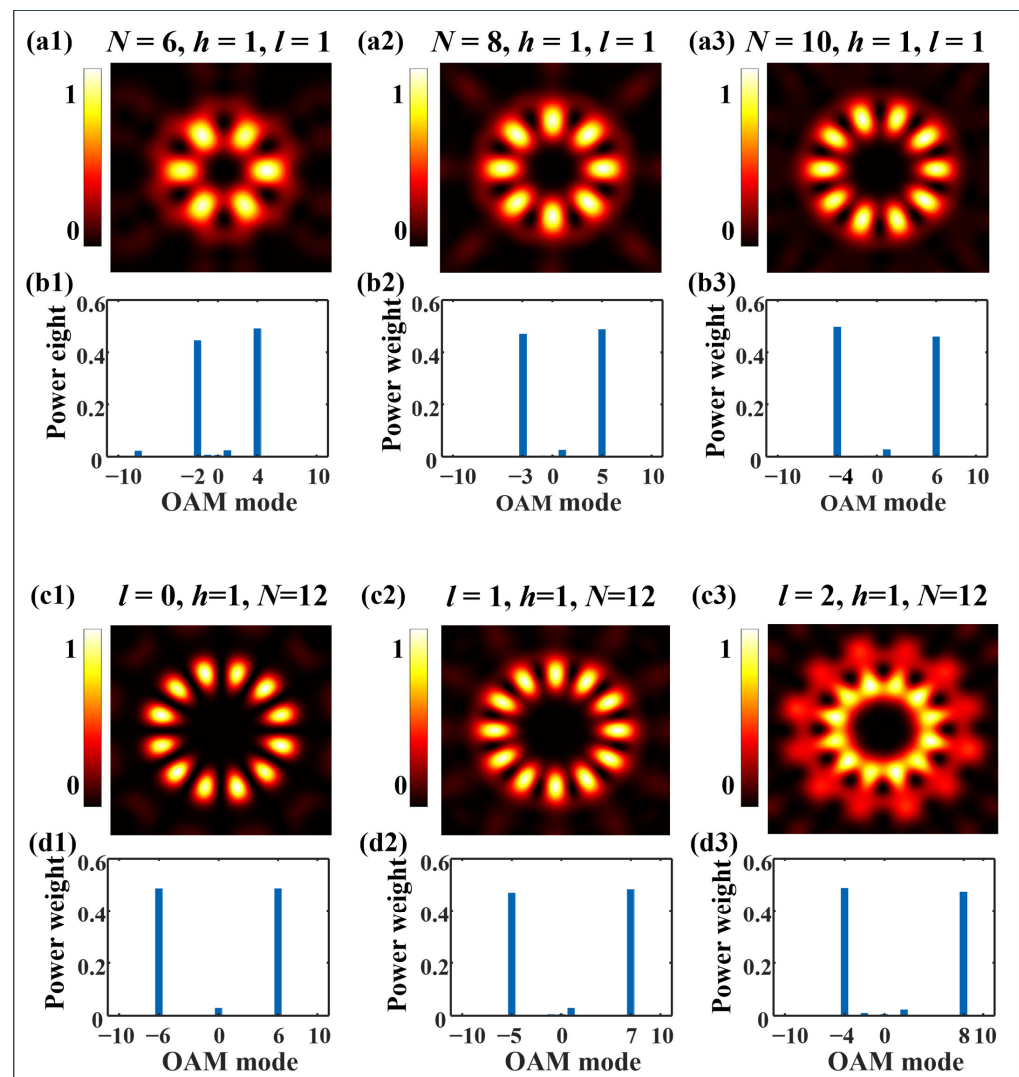


Figure 3. Simulated intensity profiles and OAM spectrum of SASZPs with different structural parameters. (a1–a3) From left to right, the structural parameters $l = 1, h = 1$, and $N = 6, 8$ and 10 , respectively; (b1–b3) OAM spectrum of (a1–a3); (c1–c3) from left to right, the structural parameters $N = 12, h = 1$, and $l = 0, 1$ and 2 , respectively; (d1–d3) OAM spectrum of (c1–c3).

Finally, assured that the number of annulus-sector primitives N and the radial misalignment parameter h remain unchanged, then we transform the parameters of the topological charge l and analyze the effect of l on the intensity distribution of the diffracted optical field and the OAM spectrum. It clearly can be seen from Figure 3(c1–c3) that the center bright spots initially distribute in a discrete and uniform manner, and as the topological charge l increases the intensity distribution has been gradually contracting towards the center, approaching each other and forming a jagged ring shape. The central dark spot remains unchanged, and the overall structure maintains rotational symmetry all the case. Consequently, we can conclude from our calculations that although the variations in the topological charge l modify the intensity distribution profile, the number of bright petal-like spots in CVBs are not verified. Interestingly, as discernible from Figure 3(d1–d3), when $h = 1$, the corresponding OAM mode spectrum is the superposition of modes $l_1 = l + N/2$ and $l_2 = l - N/2$, with the relative proportion of the two modes being approximately equal, which is consistent with the OAM spectrum for $h = 1$ in Figure 2b.

To further validate the ability of the SASZPs to generate CVBs under arbitrary circumstance, we have carried out a direct comparison between the focusing properties of SASZPs

with specific and random radial misalignment parameters. Here we select $h = 0.65$ as the special radial misalignment parameter which exhibits a high mode purity consisting of only two modes and $h = 0.30$ as the random case. It can be obviously concluded from Figure 4 that by changing the values of the topological charge l and the number of annulus-sector primitives N of the SASZPs, petal-shaped vortex beams can be both generated in the two cases. Particularly, as we discussed above, it is known to us that when the radial misalignment parameter $h = 1$, the number of petal spots in the petal-shaped vortex beam preserves the same values as that of the number of annulus-sector primitives N . Nevertheless, except for the case of radial misalignment parameter $h = 1$, we can deduce from Figure 4a,b that as the radial misalignment parameter identified, the number of petal spots in the petal-shaped vortex beam is always equal to $N/2$. Interestingly, from the investigation, we also observed that although the petal spots in the petal-shaped vortex beam are generally symmetrically discrete distributed at the center of the diffraction patterns, in some given cases such as the $h = 0.65$, $N = 10$, $l = 4$ and $h = 0.3$, $N = 14$, $l = 5$, the bright spots are no longer discrete and circular patterns have been formed.

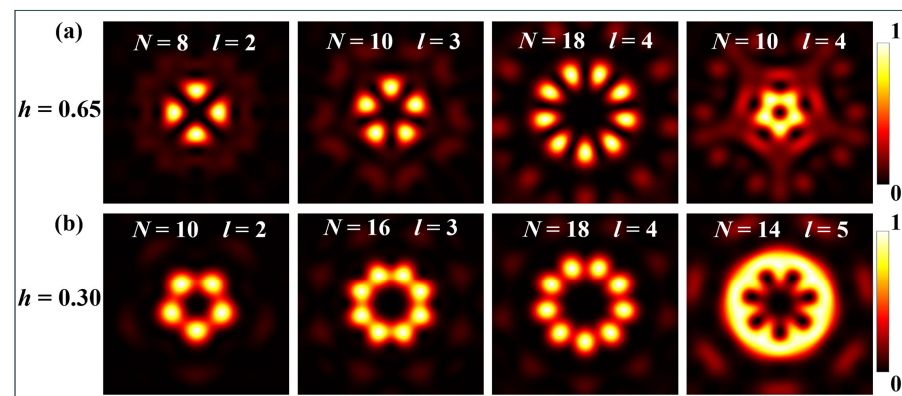


Figure 4. Simulated intensity distribution of SASZPs with different structural parameters at the focal plane. (a) From left to right, $h = 0.65$, $N = 8, 10, 18, 10$, and $l = 2, 3, 4, 4$, respectively; (b) from left to right, $h = 0.30$, $N = 10, 16, 18, 14$, and $l = 2, 3, 4, 5$, respectively.

4. Experimental Results

Further experiments were performed to verify our theoretical predictions and demonstrate our central findings. Particularly, considering that diamonds have a low coefficient of thermal expansion, such optics which have been adopted by diamond substrate would exhibit superior and stable focusing characteristics even under harsh conditions such as high temperature and high pressure. Consequently, in our investigation, we used MPCVD to coat the metal films on diamond to fabricate SASZPs with different parameters. Specifically, a 200 nm thick photoresist (PMMA) was first spin-coated on the surface of the diamond substrate, followed by a pre-baking process. Then, a conventional electron beam lithography system was employed to define the desired pattern, and electron exposure solidifies the mask profiles. After exposure is completed, to fabricate the hard mask, an 80 nm thick metallic aluminum (Al) film was deposited over the entire surface of the sample by electron beam evaporation, and selective etching transfers the mask patterns into the Al layer. Finally, lift-off removes leftover resist, leaving only the patterned Al hard mask on the diamond substrate. Figure 5(a1–a4, b1–b4) show the structures of four SASZPs with different structural parameters under a scanning electron microscope (SEM). The contours of the SASZPs and the degree of radial displacement of the sectorial primitives can be clearly observed.

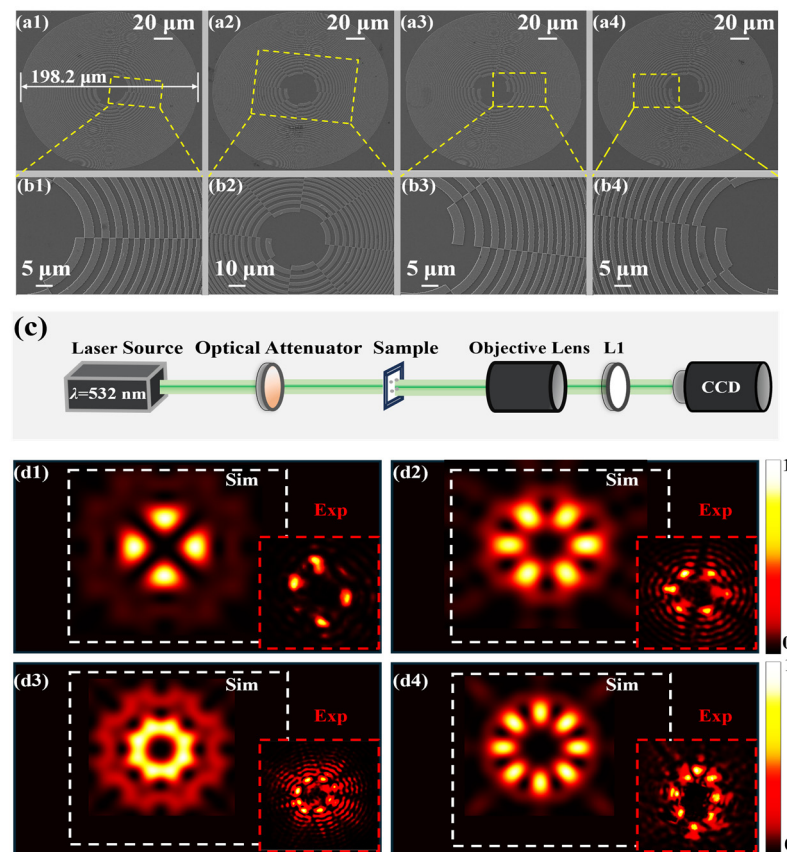


Figure 5. (a1–a4) SEM images of four different types of SASZPs; (b1–b4), SEM images of details Figure (a1–a4), from left to right, the structural parameters $l = 2, 1, 2$ and 1 , $h = 0.65, 1, 1$ and 1 , and $N = 8, 6, 8$, and 8 , respectively; (c) schematic of the verification experiment setup; (d1–d4) numerical simulation and measured intensity distribution of SASZPs, the structural parameters $l = 2, 1, 2$ and 1 , $h = 0.65, 1, 1$ and 1 , and $N = 8, 6, 8$, and 8 , respectively.

The experimental configuration is schematically shown in Figure 5c. In the experiments, the wavelength of the incident laser is 532 nm and the focal length is 245 μm , and the incident laser was vertically incident on the surface of the fabricated SASZPs sample after power was attenuated by a conventional optical attenuator. The outgoing beam was magnified by an objective lens (Olympus, LMPlanFL N20 $\times$ /0.4) and subsequently scaled by a lens with a focal length of 75 mm to ensure that the image size matched the effective area of the CCD camera (pixel size $4.54 \times 4.54 \mu\text{m}^2$, 2752×2152 pixels). Finally, the CCD camera is employed to record the focused light intensity distribution of the SASZPs. In this typical calibration, we measured the light field intensity at the focal plane of the SASZPs with different structural parameters respectively.

From the calibration results as exhibited in Figure 5(d1,d3), we can obviously observe that if the topological charge $l = 2$ and the number of annulus-sector primitives $N = 8$, by changing the radial misalignment parameter h from 0.65 to 1, it can be seen that not only the attractive focusing intensity distributions with petal-like structures in the propagation direction can be produced but also the light intensity distribution can be varied from four bright spots into a circular pattern accompanied by secondary diffraction at the same time, which accord well with the simulations as presented in Figure 2a. Interestingly, as illustrated in Figure 5(d2,d4), if the topological charge $l = 1$ and the radial misalignment parameter $h = 1$, by changing the number of annulus-sector primitives N , apart from the appearance of the focusing intensity distributions with symmetrical petal-like structures and central dark cores, the comparison also reveals that the number of bright spots of the petal-shaped light intensity is always equal to the number of annulus-sector primitives N ,

which highly matched the calculation shown in Figure 3(a1–a3). In addition, to further investigate the influence of topological charge on the diffraction patterns of the SASZPs, as presented in Figure 5(d3,d4), we also carried out the demonstration experiment as the radial misalignment parameter $h = 1$ and the number of annulus-sector primitives $N = 8$, then as the topological charge l decreased, the light intensity distribution gradually transformed from a continuous circular pattern to discrete bright spots. In addition, the light intensities at the bright spots and the secondary diffraction are gradually decreased whereas the number of the bright spots remained unchanged, which is consistent with the calculation results shown in Figure 3(c1–c3). There are still little differences in the intensity distributions, which may be caused by limited machining errors and unavoidable measurement errors. Regardless, the excellent capability of generating high-quality CVBs of our proposed SASZPs has also been effectively validated experimentally and theoretically. This methodology of generating CVBs is expected to be applied in fields such as optical communication and particle coding.

5. Conclusions

In this work, by combination of theoretical simulations and experimental demonstrations, we established an effective and straightforward methodology termed SASZPs for generating CVBs with controllable and high-purity OAM spectrum. The central idea indicated that by combining the equal-angle segmentation and radial displacement modulation approach together, we have modulated the transparent and opaque zones of the conventional SZPs and the attractive focusing intensity distributions with petal-like structures in the propagation direction can thus be obtained. Furthermore, the mode purity and the composition of the OAM of the generated CVBs can also be flexibly adjusted by controlling the parameters of optics such as the topological charge, the radial misalignment parameter and the number of annulus-sector primitives. Especially, considering diamonds have a low coefficient of thermal expansion, the diamond substrate diffractive optical elements can exhibit superior and stable focusing characteristics even under harsh conditions such as high temperature and high pressure. In our investigation, we have also fabricated the diamond substrate SASZPs samples with different parameters based on the electron beam lithography technology and dry etching technology for calibration. Relative to the optical vortices generated by the conventional SZPs, this innovation scheme, on one hand, can generate the desired number of petal-like light distributions; on the other hand, it can flexibly control and adjust spectrum with higher OAM mode purity. These findings are expected to direct a new avenue to the development of optical manipulation, optical communication, ultra-compact solar-blind UV imaging, and integrated optical systems.

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Informed Consent Statement: Written informed consent has been obtained from the patient to publish this paper.

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Conflicts of Interest: The authors declare no conflicts of interest.

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