Generation of few μm high optical vortex using tunable spiral plates

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Abstract

Optical vortices have been extensively explored, due to their widespread applications, spanning from optical trapping to laser processing. Previously, several methods for generating optical vortices had been reported. However, none of the previously reported methods demonstrated the design of a geometrically variable tunable spiral plate (SP) capable of tuning the optical vortex’s features. In this study, we present a three-dimensional tunable SP capable of generating desired vortex and focal characteristics. These SPs are 10 μm in width and 7–17 μm in height, generating few μm high vortices. We used the 3D finite difference time domain approach to model and simulate these SPs for incident plane waves with a wavelength of 632 nm. We show that the vortex profiles can be tweaked in two ways: by changing the SP’s geometrical features along the vertical axis, and by changing its refractive index.

1. Introduction

Vortices are ubiquitous in nature, ranging from tornadoes to whirlpools and even galaxies. Likewise, such vortices have been discovered to develop in electromagnetic and optical fields, which are referred to as optical vortices. An optical vortex is the simplest type of a light field capable of carrying orbital angular momentum (OAM). The concept of an optical vortex was first introduced in [1] and developments in the field of optical vortex have been reviewed in several publications [2–5]. An optical vortex is the zero point of an optical field, the point of no light [6], which is sometimes referred to as a phase singularity or screw dislocation. Light is twisted around the optical axis in optical vortices in the same way as a corkscrew is twisted [7, 8]. Due to the twisting, the light waves at the axis cancel out one another resulting in an optical vortex that resembles a ring of light with a dark core [9]. Optical vortices have gained increasing interest over the last decade due to their unique qualities of carrying OAM, including a black core, and holding a phase singularity at their core.

Optical vortex (OV) found applicability in a wide variety of areas due to their intriguing qualities, which include a robust topological structure and presence in a large number of scattering systems. Realization of OAM-entangled photon pair paved the way for applications in quantum optics and quantum information processing [10, 11]. The unique intensity profile and OAM of OVs allow use in laser applications not only to fabricate complex features such as microneedles [12] and chiral metal nanoneedles [13] but also for nonlinear frequency conversion [14] and high field laser physics [15]. In addition OV beams have been effectively used in optical tweezers because they have the benefit of capturing and spinning dielectric particles with a low index (relative to the hosting medium) in their zero-intensity zone [16–18]. In optical trapping, it has been established that OV beams, especially the Laguerre–Gaussian (LG) modes, are more dynamic than Gaussian beams [19] which enable control of both low- and high-index microparticles concurrently [20], as well as rotating absorptive microparticles [21]. The LG beam has also been found to stack microspheres around its intensity ring, therefore used to generate a three-dimensional (3D) structure [22].
The OVVs are generated in a variety of methods. Synthetic holograms [23, 24], laser mode separation [25, 26], computer-generated holograms [27], phase masking [28], hologram superimposing Bessel beams [29], holographic meta surface liquid-crystal spatial light modulator (LC-SLM) [30], phase-only SLM [31, 32], multiple plane wave interference [33], and deformable mirrors [9]. LC-SLM methods have shown to generate perfect OV [30, 34] and gradient-rotation split-ring antenna metasurfaces have shown to generate high purity OVVs [35], while the use of spiral phase plates is one of the most often used passive methods for the generation of OVVs [36–38]. Numerous ways for generating optical vortices are reviewed in [39, 40].

Conventional methods for generating OVVs do not allow effective tuning, limiting their utility as an OV generator with fixed vortex properties. This limits their functionality in a variety of applications, including optical trapping, laser processing etc. To the best of the authors’ knowledge, no work has previously described the use of tunable geometric plates for the generation and tuning of OVVs. In this paper, we present a theoretical design of a novel tunable 3D spiral plate (SP) and examine its performance using the finite difference time domain (FDTD) simulation technique. For incident plane waves of 632 nm wavelength, the SP forms an optical vortex in free space along the optical axis. These SPs have a width of 10 µm and a height of 7–17 µm. Two distinct tuning options for these SPs are proposed in order to obtain the appropriate vortex and focus properties. First, by modifying the composition during the manufacture process, which results in a variation in the refractive index. Second, by fine-tuning the geometric parameters (often along the height) to alter the SP’s periodicity. This is achieved by compressing or expanding the SP along its height (along z axis). Due to this shift in periodicity, distinct optical vortices with different heights and 3D features develop in free space. These two techniques combined allow better tunability in generating desirable vortex and focus profiles. In addition, the second technique (geometric parameter modification method) enables active adjustment of the SPs, allowing fine-tuning of the vortex profiles.

2. Design and method

To model the SPs, a full-wave 3D electromagnetic simulation was performed using the FDTD approach as implemented in Lumerial®. The SP response to an incident plane wave of 632 nm wavelength was computed for three and four turns SPs with varied periods. The plane wave propagates normally along the positive z axis (direction illustrated by red arrow in figure 2), with the electric field E pointing along the x axis. The SP period is adjustable between 2 and 3.5 µm for both three and four turns SPs. The bottom and top diameters of both types of SPs with varied period configurations were kept at 10 and 1 µm, respectively. Figure 1 illustrates the geometry of a SP with four turns. The 3D perspective image of the silver nanoparticles (NPs) doped gelatin SP is shown in figure 1(a). The SP’s vertical cross section is shown in figure 1(b) labeled with the period and bottom and top diameters. The SP's period can be modified by compressing the plate along its vertical axes, as illustrated in the transition from figures 1(b) and (c). The SP composing matrix has a refractive index of between 1.57 and 1.72. Variation of refractive index can be accomplished by altering the weight fraction of AgNO₃, doped in gelatin [41].

The 3D profiles depicted in result section 3.1 (and supplementary section S1 available online at stacks.iop.org/JPhysPhon/4/034001/mmedia) are generated by quantifying the $|E|^2$ for each cubic voxel (dimensions 0.07 µm (dx) × 0.07 µm (dy) × 0.07 µm (dz)) in the simulated region. Each map has a threshold (the lowest value on a color scale) to eliminate the background. The vortex profiles depicted in section 3.2 (and supplementary section S2) are mapped by identifying and magnifying the vortex volume's cross section. Section 3.2 makes use of the measurements taken to map the 3D profiles shown in section 3.1. The two-dimensional depth of focus maps displayed in section 3.3 are obtained by quantifying the field over the XY plane using two-dimensional monitors at the indicated depths. The line graphs displayed in section 3.4 were created using 1D data for X axis measurement (along center) of Y axis and for Y axis measurement (along center) of X axis at various depths (along positive Z plane). The aggregate normalized intensity plot is calculated by quantifying and aggregating the one-dimensional plots for both the X and Y axes from the beginning to the end of the spiral.

We used a three-monitor configuration illustrated in figure 2 to determine the throughput efficiency. A 2D transmission monitor quantifies the SP’s total throughput power along the XY plane. A 2D source monitor records the total field propagation from the source along the XY plane, as well as the back reflection from the SP. The back reflection, computed by a 2D back reflection monitor along XY plane, is subtracted from the source in order to determine the source’s absolute propagation. Throughput efficiency is measured as the ratio of throughput power from the SP to the source power.
3. Results

In figures 3–8, we illustrate and characterize the optical vortices generated with the tunable SPs. Alphabets (a)–(c) signify maps for four-turn spirals in figures 3–5 and supplementary sections S1–S5, whereas (d)–(f) denote maps for three-turn spirals at various periods. Additionally, the roman numerals (i), (ii) signify 1.72 and 1.57 refractive index values, respectively. The following sections illustrate a wide range of computed maps and plots that were used to characterize the optical vortices generated with three and four turn SPs with tunable geometrical parameters and refractive indices. All maps included in the manuscript and supplementary information have been normalized (relative to the incident plane wave) and have a base intensity of 3 (arb.) units rather than zero.

3.1. 3D maps of plane wave propagation through spiral plates (SPs)

The response of the SPs to plane wave propagation is shown in figure 3 for a variety of geometrical parameters and refractive indices, demonstrating tunable OVs as the matrix is compressed or expanded along the z-axis. Figure 3 shows 3D maps of the square of the (mod) electric field ($|E|^2$) for three- and four-turn SPs with varied periods and refractive indices. The $|E|^2$ map for a four-turn spiral with a period of 3.5 µm and a refractive index of 1.72 is shown in figure 3(a(i)). In comparison, figure 3(a(ii)) shows the $|E|^2$ map for the same number of turn and period SP but with a refractive index of 1.57. These two subfigures demonstrate the variance in the vortex profile formed as a function of refractive index change which can be achieved by the change in Ag NP concentration in gelatin. Figures 3(b(i)) and (c(i)) depict the variation in

![Figure 1. Schematic illustrating the geometry of the proposed SPs. (a) Shows the 3D perspective of the four-turn SP. (b) Shows the vertical cross section of the SP labeling, period, bottom diameter, and top diameter. And (c) shows reduction in period following the compression along the vertical axis. (Schematics not drawn to scale).](image)

![Figure 2. Three monitor configuration used for the measurement of throughput efficiency. The red arrow with the source represents the direction of source plane wave propagation along positive z axis.](image)
Figure 3. Three-dimensional maps depicting plane wave propagation through 3D SPs. The images depict the square of the electric field modulus. Subfigures (a(i)), (b(i)), and (c(i)) illustrate maps for a four-turn SP with a refractive index of 1.72 and, (a(ii)), (b(ii)), and (c(ii)) illustrate maps for SPs with refractive index 1.57, four turns, and periods of 3.5, 3, and 2.5 µm, respectively. All SPs are incident with a plane wave of 632 nm from the bottom along the z-axis.

The optical vortex formed as a consequence of changes in the SP’s geometrical parameters for periods 3.0 and 2.5 µm, respectively, both with the same refractive index of 1.72. Likewise, figures 3(b(ii)) and (c(ii)) illustrate the $|E|^2$ maps for a four-turn SP with periods of 3.0 and 2.5 µm, respectively, both with a refractive index of 1.57. Similar $|E|^2$ maps for three-turn SPs at various periods are presented in supplementary section S1, figure S1.2 for both refractive indices. Table 1 lists the total height of the SPs for various turns and periods. The height of the generated optical vortex is the distance between the top of the SP (physical structure) and the point in the z plane along the direction of propagation where intensity falls below the normalized intensity indicated by the color bar of the maps in the figures below. The z axis (vertical or height axis) value, at which integrated average intensity along the XY plane falls below the normalized intensity value is the end point of the optical vortex, corresponding to the height of the optical vortex. Supplementary section S6 shows the schema describing the method utilized for the computation.
Table 1. Table enlisting the values of depth of focus and height of the generated vortex for SPs with respective turns, period, and refractive index.

| Number of turns | Period | Height of SPs | Ref index | Depth of focus | Vortex height |
|-----------------|--------|--------------|-----------|---------------|---------------|
| 4               | 3.5    | 15           | 1.72      | 17            | 12.4          |
|                 |        |              | 1.57      | 15.5          | 15.0          |
| 4               | 3      | 13           | 1.72      | 16.5          | 15.8          |
|                 |        |              | 1.57      | 14            | 13.9          |
| 4               | 2.5    | 11           | 1.72      | 16            | 17.3          |
|                 |        |              | 1.57      | 12.5          | 17.1          |
| 3               | 3      | 10           | 1.72      | 23            | 31.6          |
|                 |        |              | 1.57      | 11            | 19.0          |
| 3               | 2.5    | 8.5          | 1.72      | 23.5          | 32.1          |
|                 |        |              | 1.57      | 10.3          | 33.6          |
| 3               | 2      | 7            | 1.72      | 24            | 32.9          |
|                 |        |              | 1.57      | 10            | 35.8          |

Figure 4. Maps illustrating variation in the vortex profile as a function of period and refractive index change. The subfigures (a(i)) and (b(i)) show the mod $E^2$ squared maps for four-turn SP at refractive index 1.72 and 3.5 and 3 $\mu$m period, respectively. Subfigures (a(ii)) and (b(ii)) illustrate the vortex profile of a four-turn SP with a refractive index of 1.57 and periods of 3.5 and 3 $\mu$m, respectively.

3.2. 3D vortex profile maps
In figure 4, we highlight the vortex profiles in space by mapping only the vortex sections. The vortex profiles and its variations, also shown in 3D maps of the square of the (mod) electric field ($|E|^2$), are mapped as a function of refractive index and period modifications. Figures 4(a(i)) and (b(i)) shows the vortex profiles for four-turn SP for periods 3.5 and 3.0 $\mu$m respectively, both with a refractive index of 1.72. Figures 4(a(ii)) and (b(ii)) shows the vortex profiles for the same number-turn spirals with the same periods 3.5 and 3.0 $\mu$m respectively, however at refractive index of 1.72. These maps are used to characteristically profile the vortexes generated and compute their heights which are plotted in the results section 3.4 and later used in analysis for
Figure 5. Field distribution maps along the XY plane at various z planes above the SP to illustrate vortex formation and profile the focal plane. Subfigures (b(i)) and (c(i)) illustrate a four-turn SP with a refractive index of 1.72 and periods of 3 and 2.5 µm, respectively. Subfigures (b(ii)) and (c(ii)) illustrate maps for a four-turn SP with a refractive index of 1.57 and periods of 3 and 2.5 µm, respectively.

3.3.2D depth of focus maps in the vortex
In figure 5, we highlight the variance in field depth (height of positive Z plane) and profile of the formed focal volume for SPs with a choice of geometrical parameters and refractive indices, by plotting field distribution along two-dimensional XY planes (slices) near the focal plane. Figure 5 shows the varying 2D profiles along the XY plane at different depths along the Z plane for four-turn SP at both 1.57 and 1.72 refractive indices. Height of the Z plane at which XY plane is profiled is mentioned at the top of each sub image. Unit of the height measurement is µm. Height z = 0 represents the base plane of the SP. The total height of each SP is listed in table 1. For example, z@15 µm for a four-turn 3.0 µm SP represents a plane that is 2 µm above the SP as height of SP is 13 µm in this case. To illustrate the variation in vortex profile as a function of change in SP
height, Figures 5(b(i)) and (c(i)) show the depth of focus maps for four-turn SP with a period 3.0 and 2.5 μm respectively, both with a refractive index of 1.72. To highlight the variation in vortex profiles as a function of change in refractive index, figures 5(b(ii)) and (c(ii)) show the depth of focus maps for four-turn SP with similar periods 3.0 and 2.5 μm respectively however, at refractive index of 1.57. Depth profile maps of other three and four turn SP at different periods and indices are shown in supplementary information section S3.

3.4. Characterization of 2D normalized field intensity plots for generated OVs

In figure 6, the $|E|^2$ intensity profiles normalized to 1 are plotted near the focal plane to demonstrate the formation of a donut-shaped profile at the focal plane, its uniformity along the X and Y axes, and the intensity profile variation as a function of the SPs geometrical parameter and refractive indices. Figure 6 shows the intensity distribution along the X and Y zero axes at mentioned Z planes along the optical axis for a four-turn SP with a 2.5 μm period and refractive index of 1.72. Each colored line in the subplot represents the normalized intensity at a particular Z plane. The Z planes are chosen so that they are located near the optical axis's maximum intensity focal plane. In figure 6, the Z planes are plotted along the optical axis in the range 17.5–19.5 μm with a step size of 500 nm. The 2D XY maps (section of figure 5(b(ii))) at similar heights is shown above the plot. Plot depicts the intensity declining to almost zero, illustrating a dark core, which denotes the singularity at the intersection of the X and Y axes (represented by a drop to zero intensity value at the center of axes). In figure 6, the disparity in the peak intensities of the positive and negative X and Y axes signifies the asymmetry in the donut focal profile. Supplementary section S4 contains normalized intensity plots for each of the remaining SP parameters discussed in this study. For several SP parameters modeled in this study, the approximate height of the maximum intensity focal plane is also listed in table 1.

The normalized intensity (normalized to 1) profile aggregated across several z planes from the top of the SP to the optical axis’s minimum intensity (end of spiral) is shown in supplementary section S5. In contrast to figure 6, supplementary figures S5.1 and S5.2 illustrates the profile of the formed optical vortex qualitatively along its length in the optical axis rather than just near the focal plane.

The line subplots in figure 7 illustrate the vortex height at various SP parameters used in the study. Subplot figure 7(a) shows the vortex height of a four-turn SP with a refractive index of 1.72 at several periods. In this case, as the period increases, the height of the optical vortex decreases. Similarly, subplot figure 7(c) shows the height of vortices formed at periods ranging from 2.5 to 3.5 μm for a four-turn SP with a refractive index of 1.57. In this case, when the period is increased from 2.5 to 3.5 μm, the height of the optical vortex fluctuates with the optical vortex height being the smallest at 3 μm period. Subplots figures 7(b) and (d)
Figure 7. Line plots illustrating the formed vortex’s heights. Subplots (a) and (c) illustrate line plots of the vortex height for a four-turn SP with refractive index 1.72 and 1.57, respectively, over a range of periods. Similarly, subplots (b) and (d) illustrate the vortex height for a three-turn SP with refractive index 1.72 and 1.57 at various periods.

Figure 8. Plots illustrating the throughput efficiency of SPs. (a) and (c) Show the throughput efficiency for four-turns plate for different periods at refractive index 1.72 and 1.57 respectively. And (b) and (d) shows the throughput efficiencies for three-turns SP for different periods at refractive indices 1.72 and 1.57 respectively.

depict the heights of optical vortices formed on three-turn SPs with refractive indices of 1.72 and 1.57, respectively. In both cases, the height of the optical vortex formed decreases as the period increases.

Subplots in figure 8 illustrate the change in optical throughput efficiency for the SPs used in this study. Subplot figure 8(a) illustrates the optical throughput efficiency of the four-turn SP with a refractive index of 1.72 at several periods. In this case, as the period increases, the throughput efficiency decreases. However, as illustrated in subplot figure 8(c), the throughput efficiency increases with a increasing period for a the same-number-of-turn SP with a refractive index of 1.57. As illustrated in subplot figure 8(b), the throughput efficiency increases with increasing period for a three-turn SP with refractive index 1.72. However, the throughput efficiency decreases as the period increases for a refractive index of 1.57.

4. Discussion

The study demonstrates an innovative method for generating and controlling few micrometers (µm) high optical vortexes using a high efficiency tunable SP. The tunability is achieved through structural and
refractive index variations of the SP. Three-dimensional FDTD theoretical modeling results have revealed useful insights into tuning the behavioral response and geometric profile of the formed optical vortex. Mahmoud and Abbo [41] demonstrated that the refractive index and band gap can be tuned between 1.57 and 1.72 by varying the weight percentage of silver NPs in the gelatin. Kang et al reported the use of femtosecond pulse processing to fabricate in a similar compositional material [42]. In this article, we examined SPs with three and four turns and periods ranging from 2 to 3.5 µm. Both SPs with three and four turns and respective periods are modeled using refractive indices of 1.72 and 1.57.

4.1. Effect of the variation in the SPs period on the vortex profile
Figure 3 illustrates the tunable behavior of the four-turn SP by mapping the $|E|^2$ response. All maps are plotted on the same color scale to establish the distinction. Along with the spatial profile of the formed optical vortex, the height of the vortex is used to characterize its geometrical variation as a function of period. The differences in the spatial profiles of the optical vortex formed in the case of a four-turn SP as the period changes from 2.5 to 3.5 µm are illustrated in figure 3. Additionally, figure 4 emphasizes the vortex's sectional profile. For both refractive indices 1.72 and 1.57, compression in the four-turn SP altered the geometrical profile of the formed optical vortex. This shift in the spatial profile of the formed optical vortex could well be attributed to a shift in the spacing between the diffracting surfaces along the optical axis. It is observed that the height of the formed optical vortex decreases with increasing period for both three and four turn SPs, with the exception of a four turn SP with a period of 3 µm and a refractive index of 1.57, as shown in figure 7. As diffractive surfaces become closer together (due to compression), the propagating field concentrates (makes a greater contribution) along the optical axis, resulting in higher vortices. Due to the fact that the focal plane profile is inherently a function of the optical vortex spatial profile, the period of the SPs also affects the focal plane profile. A donut-shaped profile with a dark core is observed at all focal planes formed at different periods, ref index, and turns of SPs, as shown in figures 5 and 6, and supplementary sections S3 and S4. This further corroborates the optical vortex's existence [33, 43].

4.2. The effect of the refractive index of the SP on the vortex profile
Figures 3(a(i)), (b(i)), and (c(i)) compared the spatial vortex profile (response) of a four-turn SP with a refractive index of 1.72 to that of a four-turn SP with a refractive index of 1.57 for periods of 3.5, 3.0, and 2.5 µm, respectively. This variation in the vortex profile is a result of the refractive index differential and thus the diffraction properties. Although the spatial profile of the vortex varies significantly with refractive index change for both three and four turn SPs over all periods, no significant variation in the height of the formed vortex is observed, as illustrated in figure 7. Instead, the effect of differential refractive index is more pronounced in throughput efficiency, as showed in figure 8. The throughput efficiency of both three and four turn SPs is significantly higher in the case of ref. index 1.57 compared to 1.72.

4.3. The effect of SP turns on the profile of a vortex
Due to the fact that period affects the spacing between diffractive surfaces, the number of turns in the SPs determines the number of diffractive surfaces contributing to vortex formation. The supplementary sections S1–S3 illustrate the vortex spatial and focal profiles for three turn SP (and compare them to four turn SP). Vortex formation follows the same mechanism for three and four turn SPs and is a function of period and refractive index. However, the reduced number of diffractive surfaces in three turn SPs results in the formation of optical vortices nearly twice the height of those in four turn SPs at all periods and ref indices. The number of diffractive surfaces or turns in SP has no discernible effect on the efficiency of the throughput.

5. Conclusions
In this paper, we presented a novel high-efficiency 3D tunable SP design capable of generating optical vortices up to a few µm in height with focusing capabilities. The proposed SP design generates optical vortices with tunable focusing capabilities. Unlike other optical vortex generating 2D structures, the proposed 3D structures allow for tunability via mechanical stimulus (tensile or compressive) or chemical composition variation, which can be accomplished using a variety of experimental methods. In SPs, it is demonstrated that the spatial and geometrical properties of the generated optical vortices, as well as the depth of focus, are all tunable in two ways. First, compress the SP geometrically to alter its period. This can be achieved through external stimuli. Second, by varying the weight percentage of AgNO$_3$ in gelatin used to prepare the sample, the effective refractive index of the SP can be altered. By fabricating such optical devices, it is possible to create SPs with active tuning capabilities, paving the way for further applications in tweezers, optical trapping, and so on. This study broadens the application possibilities of SPs in devices with an active tunability requirement and provides further insights for design of zone plates with tunable properties.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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