Comparative simulation of spiral zone plates with a relief from silica glass and silver

E S Kozlova¹², V V Kotlyar¹²

¹Image Processing Systems Institute of RAS - Branch of the FSRC "Crystallography and Photonics" RAS, Molodogvardejskaya street 151, Samara, Russia, 443001
²Samara National Research University, Moskovskoe Shosse 34A, Samara, Russia, 443086

e-mail: kozlova.elena.s@gmail.com

Abstract. Comparative simulation of optical vortices generation by spiral zone plates with a relief from silver and silica glass using a frequency depended finite difference time domain method. The right circularly polarized Gaussian pulse was used as incident light. An analysis of the Umov-Poynting vector, amplitude and phase distributions in the focal plane shows was the presence of complex optical vortices with an inverse energy flow in its' centre. Influence of the amplitude spiral zone plate relief height on energy backflow is studied. Comparison of simulation results for two types of spiral zone plate confirms the possibility of using the amplitude analogue instead of the phase zone plate since it is simpler to manufacture.

1. Introduction
In recent years, optical vortex [1-4] has drawn much attention because of their widespread application in various areas, such as optical communication [5], optical micro-manipulation [6], optical micro-measurement [7], and materials processing [8]. Optical vortex can be generated by special optical element which embed phase singularity into ordinary laser beam [9-15]. In [10] the apodizing spiral zone plate (SZP) with Bessel functions was theoretically and experimentally investigated. Theoretically, studies utilizing scalar diffraction integrals showed generation of hypergeometric beams. Influence of the order of the Bessel functions and topological charge on generation of focused beams was examined. Simulation and experimental results were in very good agreement with each other. The high-efficiency polarization independent dielectric metasurfaces for generating the coaxial focusing optical vortex beams, multi-channel focusing optical vortex beams, the abruptly focusing airy beams and the abruptly focusing airy optical vortex beams and resolving the orbital angular momentum was considered in [11]. The element was calculated for infrared range (λ = 1.55 µm) and consisted of amorphous silicon (n = 3.57) nanoposts with the radii of 50-250 nm deposed on silica glass (n = 1.45). A series of Pancharatnam-Berry phase elements were designed in [13] to produce the perfect vortex and vector beams. Vectorial beams on the wavelength of 633 nm with the topological charges of 1, 2, 3 and the light rings whose diameter does not depend on the topological charge are formed by a spiral zone plate, an axicon, and a zone plate (ZP). The size of the elements was 6 mm and the focal length of the lenses was 200 mm. A high-efficiency dielectric metasurface for a three-dimensional volumetric optical vortices generation is presented in [15]. An approach to generate
optical vortex with large topological charge based on low-order spiral phase plates (SPPs) was presented in [16]. Authors presented the optical scheme which realized the addition of topological charges by cascading multiple SPPs and doubling of topological charges by the double-pass configuration. Based on the combination of cascaded and double-pass configuration, an optical vortex with topological charge as high as 28 is generated, using two SPPs of topological charge 6 and 8, respectively. In [17] a methodology to realize an optical vortex with arbitrarily long focus-depth is provided. By varying each zone area of a phase SZP authors obtained optics for generation of ultra-long focus-depth optical vortex from a plane wave. The focal property of such optics was analyzed using the Fresnel diffraction theory, and an experimental demonstration was performed to verify its effectiveness.

In this paper, comparative modeling of SZPs with relief from silver and silica glass is presented. Simulations was carried out by frequency-dependent finite-difference time domain method ((FD)2TD-method) implemented in the FullWAVE software package. In first section, design and simulation parameters are described. Next, the detailed analysis of amplitude, phase, and intensity for each electric field component for phase SZP and silver SZP is presented. It proves presence of optical vortex with complex topological structure. The last section of the paper is devoted to the additional study of Umov-Pointing vector which showed presence of energy backflow in central part of optical vortex.

2. Design and parameters of SZP
According to formula of transmittance function [12] we calculate the binary relief of silver SZP with topological charge \( m = 2 \), diameter of 8 µm, and focal length of 532 nm. In our study we compare phase SZP from silica glass and amplitude SZP in thin silver film, which is proposed to be deposed on substrate from silica glass. The relief height for phase SZP and silver SZP is 532 nm and 100 nm, respectively. The calculated amplitude SZP is presented on Figure 1.

![Figure 1. Proposed amplitude SZP.](image)

The Gaussian beam at wavelength of 532 nm with right circularly polarization (RCP) and a waste of 4 µm is used as incident light. All simulation is carried out by (FD)2TD-method implemented in the FullWAVE software package. This method use the Sellmeier's permittivity model for silica glass [18]. The dielectric permittivity of silver is described by the Drude-Lorentz model [19, 20].

The computation was conducted at steps of 15 nm and 7 nm along transverse and longitudinal coordinates. The temporal step \( c\Delta t \) was chosen equal to 5 nm according to the Courant condition. These steps ensure the convergence of the numerical method, and a further reduction of steps does not lead to significant changes (the standard deviation of 0.001%). While analyzing simulation results the averaging of the calculated field intensity for 20 periods was done.

3. Simulation results for the SZP from silica glass
In this Section, simulation results for phase SZP is presented. To study simulation results in more details the amplitude and the phase for each electric field component were calculated by using
MATLAB script. Fig. 2 contain the distribution of the amplitude and phase of the electric field vector components in the focal plane $f = 0.532 \, \mu m$ at the time $cT = 19.82 \, \mu m$.

![Figure 2](image)

**Figure 2.** The amplitude (a-c) and the phase (d-g) distribution for electric field components $E_x$ (a,d), $E_y$ (b,f), $E_z$ (c,g) formed in focal plane ($f = 532 \, \text{nm}$) by SPZ from silica glass.

It can be seen from Fig. 2 that the SZP formed a vortex beam with a complex topological charge. The transverse components ($E_x$ and $E_y$) topological charges match the topological charge of SZP: $m = 2$ while for longitudinal component ($E_z$) it is $m = 1$.

4. **Simulation results for the silver SZP**

In this Section, simulation results for SZP with silver relief of 100 nm is presented. As in a previous case, we present amplitude and phase distribution of the electric field vector components in the focal plane $f = 0.532 \, \mu m$ at the time $cT = 19.82 \, \mu m$ on Fig. 3.

![Figure 3](image)

**Figure 3.** The amplitude (a-c) and the phase (d-g) distribution for electric field components $E_x$ (a,d), $E_y$ (b,f), $E_z$ (c,g) formed in focal plane ($f = 532 \, \text{nm}$) by SPZ from silver.

It can be seen from Fig 3. that silver SZP also produce optical vortex with the same structure as phase SZP. It can prove that silver SZP can easily substitute its phase analogue.
5. Investigation of the Umov-Pointing vector

In [21], the behaviour of the longitudinal component $S_z$ of the Umov–Pointing vector was considered while the focusing of an optical vortex by phase SZPs with topological charges $m = \pm 1$ and $m = \pm 2$. We also conducted a similar study which results are shown in Fig. 4. It should be noticed that the longitudinal component of the Umov-Poitning vector is formed by the transverse distribution of the electric ($E_x$ and $E_y$) and magnetic fields ($H_x$ and $H_y$):

$$S_z = \text{Re} \left[ E_x H_x^* - E_y H_y^* \right]$$

(1)

It can be seen from Fig. 3 that silver SZP can form the energy back flow in the case of using right circularly polarized Gaussian beam as incident light. However, it is smaller in comparison with the reverse flow formed by the phase SZP. Moreover, the qualitative distribution of the longitudinal component $S_z$ of the Umov-Pointing vector also differs. In particular, the side lobes decrease.

To analyse this phenomenon the distribution of the Umov-Pointing vector along direction of propagation and in focal plane was plotted in Fig.4. Arrows which are laying on the intensity distribution show the direction of Umov-Pointing vector.

![Figure 4](image-url)

**Figure 4.** Distribution of the longitudinal component of the Umov–Pointing vector formed in focal plane ($f = 532$ nm) by SPZs from silica glass (a) and from silver (b).

![Figure 5](image-url)

**Figure 5.** Directions of the Umov-Poynting vector plotted on intensity distribution in the XZ (a) and XY (b) plane.

Fig. 5 (a) shows the energy backflow near the optical axis. Spiral flux around optical axis can be seen in Fig. 5 (b). The analogous results have been obtained by for phase elements in [22,23].

6. Influence of the amplitude SZP relief on energy backflow

In previous section, it was shown that amplitude SZP as its phase analogue can form reverse energy flow. However, the absolute value of the longitudinal component $S_z$ of the Umov-Pointing vector is much smaller. Therefore, we investigate several design of silver SZP which differs in relief height to evaluate influence of this parameter of optical element on formation of energy flow. Fig. 6 shows the
distribution of the longitudinal component $S_z$ of the Umov-Pointing vector the intensity distribution along optical axis ($x = 0, y = 0$).

![Figure 6](image)

**Figure 6.** Distribution of longitudinal component $S_z$ of the Umov-Pointing vector (a) and the intensity distribution (b) for relief height of 70 nm, 100 nm, and 150 nm.

It can be seen from Fig. 6(a) that the value of longitudinal component $S_z$ of the Umov-Pointing vector is proportional to the value of the relief height, i.e. the reverse energy flow is more visible for the smallest height of SZP ($h = 70$ nm). Moreover, from some values of height the reverse energy flow is absent ($h = 150$ nm).

In addition, we also check the intensity of formed electric field, which distribution along optical axis is presented on Fig. 6(b). It can be seen that it has inverse proportion to relief height. Therefore, it means that the main impact on longitudinal component of the Umov-Poiting have magnetic field.

7. Conclusion

In this paper, comparative modeling of SZPs with relief from silver and silica glass is presented. Simulations was carried out by frequency-dependent finite-difference time domain method ((FD)TD-method) implemented in the FullWAVE software package. The Gaussian laser beam with right circular polarization and wavelength of 532 nm is used as incident light. Phase and amplitude of each electric field vector component was calculated during analysis of the simulation results. It is shown that the silver SZP allows to generate optical vortices. Analysis of the Umov-Pointing vector shows presence of the reverse energy flow in the focus. Moreover, it is shown that the value of longitudinal component $S_z$ of the Umov-Pointing vector is proportional to the value of the relief height while intensity of electric field has inverse proportion to it.

8. References

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