Simple and Efficient Realization of Transverse Linear Dark Beams by Azimuthal Phase-Shifted Square Zone Plate

Shahrbano Asghari

Urmia University

Arash Sabatyan (✉ a.sabatyan@urmia.ac.ir)

Urmia University <https://orcid.org/0000-0002-4447-0376>

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Simple and efficient realization of transverse linear dark beams by azimuthal phase-shifted square zone plate

Shahrbanoo Asghari · Arash Sabatyan*

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Abstract Herein, we are about to introduce a novel, reliable and straightforward method to create controllable dark lines employing an azimuthal square zone plate. As a matter of fact, this diffractive element is a square zone plate whose zones are phase-shifted azimuthally. As we illustrate, one way to construct it is combining a square zone plate and radial grating having period m . Considering its focusing behavior, we came to the result that a dark line surrounded by linear bright zones is generated for odd m , as well as a cross-like dark zone is produced when m is even. Furthermore, we illustrate that the length of the dark lines depends on the grating period. Finally, the simulation predictions are verified by experimental results.

1 Introduction

Fresnel zone plate (*FZP*) is the well-known diffractive optical element that is circularly symmetric and composed of alternating dark and light zones arranged in a quasi-periodic way. Needless to say that it has found many applications in science and technology, for example, X-ray applications [1], structuring the light [2], metrology [3], vision optics [4], terahertz imaging [5], and beam shaping [6]. Undoubtedly, FZP and FZP-based elements have opened up new, simple, cost-effective, reliable, and impressive techniques for manipulating light by modifying its phase profile within the scalar diffraction regime, as we consider here.

Based on it, a variety of zone plates in different geometries such as fractal [7], square [8], polygonal [9], elliptical [10], cross-like [11], spiral zone plate

A. Sabatyan
Physics Department, Faculty of sciences, Urmia University, Urmia, Iran
E-mail: a.sabatyan@urmia.ac.ir

Sh. Asghari
Physics Department, Faculty of sciences, Urmia University, Urmia, Iran

[12], and petal-like zone plate [13] have been introduced in order to provide a simple and easy way to implement a zone plate in many applications that are very hard or even impossible to reach via refractive optics.

Among them, a square zone plate (*SZP*) is considered over which circular zones are interchanged with square ones. Although circular *FZP* has a more desirable focusing performance than *SZP*, being more robust to fabricate *SZP* concerning fabricating imperfections than an *FZP*, make them a severe and substantial alternative to *FZPs* for their integration in optoelectronics, integrated optical circuits, micro and nano-optics [14,15].

Hence, some techniques were proposed to improve its efficiency [16,17]. Furthermore, there have been reported some applications of *SZP* in, for example, infrared detectors [18], Cassegrain concentrator [19], solar energy systems [20], rectangle multi-array focusing[21], and unique rectangle array of structured beam [22].

Azimuthal modulated diffractive elements have been demonstrated play paramount role in beam shaping and structuring [23,24]. As a consequence, it was examined that imposing the modulation on 1D FZP enable it to generate lateral linear structured beams carrying fractional topological charge [24]. Based on it, we aim to present and study azimuthal modulated square zone plate (*ASZP*) composed of angular regions having π phase difference than their immediate neighbors. At the same time, it is shown that the element is built utilizing a square zone plate and radial grating. Thereafter, scrutinizing its focusing behavior revealed that a single horizontal or double perpendicular dark line is generated at the focus provided that the azimuthal period of the grating is odd or even, respectively. Further meticulous analysis indicates that the length of the line is associated directly with the grating period. On the other hand, the length of dark line diminishes by increasing the period. Last but not least, we deem this method highly influential in improving precision alignment procedures [25–27] and also may conveniently be implemented in guiding cold atoms and particle trapping [28,29].

2 Theoretical Discussions and Computational Result

Having introduced the azimuthal square zone plate, we are about to describe it mathematically. So, one way to define its binary transmittance may be given as

$$t_s(x', y') = 0.5 \left(1 + \text{Sgn} \left\{ \sin \left[\frac{-i\pi \max(x'^2, y'^2)}{\lambda f} \right] \right\} \right) \quad (1)$$

where λ , f , and r are the wavelength of the incident light, focal length, and the radius of *ASZP*, respectively. Moreover, (x', y') denotes Cartesian coordinates at the element plane, and *Sgn* is the sign function. At the same time, the transmittance of a radial binary grating is proposed as

$$t_g(x', y') = 0.5 \left\{ 1 + \text{Sgn} \left[\sin(-im\theta) \right] \right\} \quad (2)$$

in which m is an integer. Herein, $\theta = \tan^{-1}(y'/x')$ is azimuthal angle. Finally, the transmission function of the azimuthal square zone plate may be expressed as

$$T(x', y') = \text{mod}(t_s + t_g + 1, 2) \quad (3)$$

where mod is the modulo operation.

To visualize the structure of ASZP, some samples of SZP, and ASZPs having constructed with different m is displayed in the first row of Fig. 1. As a matter of fact, these representations are to figure out that the azimuthal modulation transforms an SZP into angular multi-section element in which the subsequent sections have a π phase difference.

Numerical computations rely on the FFT-based (fast Fourier transform) method[19]. To this end, one may rewrite Fresnel– Kirchhoff integral using the *FFT* convolution theorem as the following [30]

$$I(x, y; z) = \left| F^{-1} \{ F[T(x, y)] \} \left\{ F \left[e^{ik \left(\frac{x^2 + y^2}{2z} \right)} \right] \right\} \right|^2 \quad (4)$$

where F and F^{-1} denote for fast Fourier transform and an inverse fast Fourier transform, respectively. Moreover, $k = \frac{2\pi}{\lambda}$, and (x', y') is Cartesian coordinate at the ASZP plane. Obviously, the intensity distribution at a distance z from an ASZP is written as

$$I(x, y; z) \propto |U(x, y; z)|^2 \quad (5)$$

Until now, we have mathematically introduced the idea of the ASZP, following that, surveying diffractive properties of the element is carried out for samples having side length 6 mm and focal length 500 mm, which are under the illumination of a plane beam with wavelength $\lambda = 632.8 \text{ nm}$. So, the first study is allocated to the three samples showed in Fig. 1. Invoking sequential regions having π phase difference and the same area, we expect to observe single dark lines for odd m and two orthogonal dark lines when m is even, as demonstrated in the second row of Fig. 1. In other words, these dark lines are surrounded by bright areas thus, they may called otherwise lateral optical corridors.

In order to verify the simulation predictions, the corresponding samples in simulations were photolithographically printed as a high-resolution binary mask and installed in the midway of the spatial filter-based telescope set-up lightened by He-Ne laser with the central wavelength 632.8 nm, as depicted in Fig. 2 to verify the simulation results by experiment. Accordingly, the focused intensity of the regarded samples in Fig. 1 was recorded and shown in the third row of Fig. 1 which, resembles the simulation ones.

On top of all that, the effect of the azimuthal parameter (m) on the produced patterns is studied. To this end, some samples of ASZP modulated by $m=4, 8, 16$, and $m=5, 11, 15$ are considered. Accordingly, their point spread

Fig. 1 Comparison of *SFZP* with *ASFZP*. The first row, respectively from left to right, the *SFZP* ($n = 0$), *ASFZP* with angular divisions $m = 1$ and $m = 2$. The second row, the transverse intensity distributions corresponding to these zones.

function (PSF) is examined theoretically and by experiment. As a result, scrutinizing the structure of *ASZP* depicted in the first row of Figs. 3 and 4 clarify the point that the number of delicate structures increases. Hence, we expect severe diffractions, which leads to shortening the length of the lateral dark lines. This is clearly shown in the second and third row of Figs. 3 and 4, where the focused intensity for the considered m is displayed. Resultantly, the larger m , the shortened dark lines are created.

In summary, we have demonstrated that imposing azimuthal modulation through a radial grating on a square zone plate enable us to create lateral 1D dark beams. Accordingly, these dark lines were shown to be a single or two orthogonal ones depending on the phase shift period is odd or even, respectively. further delving into *ASZP* behavior revealed the point that the great

Fig. 2 Schematic of the optical setup utilized to verify the simulation results.

period of the grating causes the finer structures are produced, therefore the length of the dark lines are reduced owing to severe diffraction from the finer portions.

3 Declarations

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Fig. 3 The first row reveals the structure of some samples of ASFZP modulated with various $m=4, 8$, and 16 from left to right, respectively. The second and third show the corresponding simulation and experimental recorded intensity at the focal plane, respectively.

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Fig. 4 The first row reveals the structure of some samples of ASFZP modulated with various $m=5, 11$, and 15 from left to right, respectively. The second and third show the corresponding simulation and experimental recorded intensity at the focal plane, respectively.

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