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Shaping a far-field optical needle by a regular nanostructured metasurface

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ABSTRACT

A new method is proposed for shaping a far-field uniform optical needle based on a regular nanostructured metasurface, viz. high-NA (numerical aperture) micro-Fresnel zone plate (FZP). The designed microstructure is comprised of two planar FZP-fragments with different focal lengths. Delicate interference of diffracted beams results in an optical needle at a required working distance in the post-evanescent field. For a 44.88 μm-diameter microstructure illuminated with a linearly x-polarized beam, a 5.77λ-long uniform optical needle is produced at a distance of 12.88λ away from the mask surface. The transverse beam sizes are 0.97λ and 0.39λ in x and y directions, respectively. The designed result calculated by the vectorial angular spectrum theory is in good agreement with the rigorous electromagnetic calculation using the three-dimensional finite-difference time-domain (3D FDTD) method. The designed microstructure is easy-to-fabricated with required NA and working distance. The proposed method can be readily modified for other polarized beams. These far-field uniform optical needles potentially suit the fields of nanolithography, optical trapping, and microscopy.

1. Introduction

Modulation of a non-diffraction optical beam or a sharp optical needle has been widely studied recently [1–7]. Different methods have been proposed, which can be primarily classified into three kinds, based on a lens refraction system [1,2], a mirror reflection system [3,4], and a nanostructured metallic-film-coated plate (or metasurface) [5–7]. Among these methods, the use of a nanostructured metasurface is more attractive and exhibits unique advantages. The metasurface is a single planar, lens-free focusing structure and it obtains far-field sub-diffraction and super-resolution without near-field evanescent waves [8–10]. However, there are still two limitations for this approach [5–8]. Firstly, focusing light needles by nanostructured metasurfaces is designed from randomly distributed microstructures with a number of annuli and it usually requires time-consuming optimization [5–8,11]. Secondly, the light field behind the metasurface is found to be very sensitive to each annulus and a binary phase-type metasurface may not work properly [12]. The essence of these drawbacks is due to that the optimization design is beginning from an irregular multi-annular structure. Besides, the non-diffraction beams, like Bessel beams and Mathieu beams, are important ways to generate a thin needle of light [13,14]. Catenary optics also paves a new road to realize non-diffraction beams [15,16].

In contrast, a binary amplitude-type Fresnel zone plate (FZP) is considered to be one kind of regular metasurface with defined zone radii, which suits a variety of applications, e.g. in atomic optics, X-ray nanoscopy, confocal imaging, and synchrotron radiation experiments [17–20]. In this paper, a uniform optical needle is to be modulated based on a binary high-NA (numerical aperture) micro-FZP with a required working distance. The designed microstructure is easy-to-fabricated with only a small amount of annuli and a defined numerical aperture. The proposed method can be used for linearly, circularly, or radially polarized beams and the illumination wavelength can be chosen from X-ray to visible.

2. Method

2.1. Fresnel zone plate

For a standard Fresnel zone plate, the radial coordinates of each annulus are determined by [18].

$$r_n = \sqrt{n\lambda f + n^2\lambda^2/4}, \quad n = 0, 1, 2, \ldots, N, \tag{1}$$

where, f is the main focal length and N is the total annulus number. λ is the light wavelength in the medium where FZP is immersed. $\lambda=\lambda_0/\eta$. λ_0 is the illumination wavelength and η is the refractive index of the immersion medium. The numerical aperture of a FZP can be defined by NA=$\eta\sin\alpha$. α is the maximum semi-angle of the focused light cone and $\tan\alpha = r_N/f$.

For a given wavelength λ, the relation of f, η, N and NA is

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determined by

$$f = \frac{\lambda N}{2(\eta/\sqrt{\eta^2 - \mathrm{NA}^2} - 1)}. \tag{2}$$

The diameter of a FZP is $D = 2r_N = 2f\cdot\mathrm{NA}/\sqrt{\eta^2 - \mathrm{NA}^2}$. According to Eq. (2), for a given working distance (f) and a required numerical aperture (NA), the annulus number (N) can be obtained. The wavelength and refractive index are usually predefined for a practical problem.

For a binary amplitude-type FZP, the transmission function,$t(r)$can be described as

$$t(r) = \begin{cases} 1, & r_{2m} < r \le r_{2m+1} \\ 0, & r_{2m+1} < r \le r_{2m+2} \end{cases}, \tag{3}$$

where, m=0, 1, ..., $N/2-1$ and N is supposed to be an even number. In Eq. (3), the innermost annulus is assumed to be a transmitting zone.

2.2. Microstructure design

The new microstructure is composed of two FZP-fragments with different focal lengths f_1 and f_2. f_2 slightly shifts f_1. The main idea is to form a light needle by delicate interference of coherent light beams diffracted from two FZP-fragments.

The construction procedure for the new microstructure is as follows:

Step 1: for a given focal length f_1 and wavelength λ, the radius sequence of the first zone plate is

$$r_{1,n} = \sqrt{n\lambda f_1 + n^2\lambda^2/4}, \quad n = 0, 1, 2, \ldots, N_1, \tag{4}$$

where, N_1 is an even number.

Step 2: choose a focal shift Δf ($|\Delta f| \ll f_1$), yielding the second focal length

$$f_2 = f_1 + \Delta f, \tag{5}$$

so, the radius sequence of the second zone plate is produced according to

$$r_{2,m} = \sqrt{m\lambda f_2 + m^2\lambda^2/4}, \quad m = 1, 2, \ldots, N_2, \tag{6}$$

where, N_2 is an even number.

Step 3: select an odd number n_i and an even number n_o, satisfying $1 \le n_i < n_o \le N_1$.

Step 4: divide the radius sequence $\{r_{2,m}\}$ into two sub-sequences, viz. an even sequence $P = \{r_{2,2}, r_{2,4}, \ldots, r_{2,N_2}\}$ and an odd sequence $Q = \{r_{2,1}, r_{2,3}, \ldots, r_{2,N_2-1}\}$; choose a number $r_{2,i}$ from P, which is the first number larger than r_{1,n_i}; choose a number $r_{2,o}$ from Q, which is the last number smaller than r_{1,n_o}.

Step 5: replace the sequence $\{r_{1,n_i+1}, r_{1,n_i+2}, \ldots, r_{1,n_o-1}\}$ of the first zone plate by $\{r_{2,i}, r_{2,i+1}, r_{2,i+2}, \ldots, r_{2,o}\}$ from the second zone plate, resulting in a new radius sequence denoted by $F = \{r_{1,1}, r_{1,2}, \ldots, r_{1,n_i}, r_{2,i}, r_{2,i+1}, r_{2,i+2}, \ldots, r_{2,o}, r_{1,n_o}, r_{1,n_o+1}, r_{1,n_o+2}, \ldots, r_{1,N_1}\}$, corresponding to a new microstructure.

Step 6: the transmission function $t(r)$ for the new microstructure is a piecewise function: $t(0 \le r < r_{1,n_i}) = 0$, corresponding to a center-obstructed circle; $t(r_{1,n_i} \le r < r_{2,i}) = 1$, corresponding to the first transmitting annulus; from r_{1,n_i} to the outmost radius r_{1,N_1}, the transmissions are consecutively varying from 0 to 1.

So, a new microstructure composed of two FZP-segments has been constructed from the above procedure, as shown in Fig. 1. There are three areas comprising this new microstructure. In the center, a center-obstructed circle is assumed to block the paraxial beams in order to sharpen the transverse beam size and extend the axial beam size. In the middle, a FZP-segment related with f_2 is intentionally inserted into another FZP-segment related with f_1. In the constructed microstructure, there are two FZP-fragments, as shown in Fig. 1. One is related with f_1 and the other with f_2. So, according to Eq. (1) and the construction procedure, all radial widths of the rings are rigorously different. As high-NA micro-FZPs are used, the polarization effect should be considered [11,12]. Here, the vectorial angular spectrum (VAS) theory is used to describe the electric field of light behind the microstructure [11,12,21]. Parameters $\{n_i, n_o, \Delta f\}$ are adjusted to precisely modulate a uniform light needle. They can be accurately determined using a suitable optimization program, e.g. genetic algorithm [11,12,21]; however, it is found through calculations that they can be quickly set only by a small refining program with several trials.

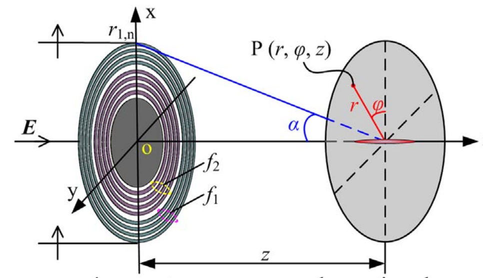

Fig. 1. Schematic diagram of focusing a light needle by the designed microstructure illuminated with an x-polarized LPB.

2.3. Calculation of the light field

According to the VAS theory, the integral representations for the electric field behind a multi-annular microstructure are briefly outlined for a linearly polarized beam (LPB) below [12]. Integral representations for a circularly or a radially polarized beam can be found in [11,12].

For an x-polarized LPB normally illuminating a planar microstructure, as shown in Fig. 1, components of the electric field $\boldsymbol{E}$ for any point $P(r, \varphi, z)$ in the observation plane ($z > 0$) are described as

$$\begin{cases} E_x(r, z) = \int_0^\infty A_0(l)\exp[\mathrm{j}2\pi q(l)z]J_0(2\pi lr)2\pi l dl \\ E_y(r, z) = 0 \\ E_z(r, \varphi, z) = -\mathrm{j}\cos\varphi \int_0^\infty \frac{l}{q(l)}A_0(l)\exp[\mathrm{j}2\pi q(l)z]J_1(2\pi lr)2\pi l dl \end{cases}, \tag{7}$$

where, $q(l) = (1/\lambda^2 - l^2)^{1/2}$ and l is the radial spatial frequency component. J_0 and J_1 are the zeroth and first order Bessel functions of the first kind, respectively. $A_0(l)$ in Eq. (7) is expressed as $A_0(l) = \int_0^\infty t(r)g(r)J_0(2\pi lr)2\pi r dr$. $t(r)$ and $g(r)$ denote the transmission function of the microstructure and the amplitude distribution of the illumination beam, respectively. $g(r) = 1$ has been assumed here. The total electric energy density (or light intensity) is calculated by $I(r, \varphi, z) = |\boldsymbol{E}(r, \varphi, z)|^2 = |E_x(r, z)|^2 + |E_z(r, \varphi, z)|^2$. A fast Hankel transform algorithm is programmed to fundamentally accelerate the calculation of Eq. (7) [11,12], which assures the efficient design of microstructures. For an x-polarized LPB, the longitudinally polarized component E_y is naught in the y direction. So, it can be implied that the light beam in the x direction will be generally wider than that along the y direction.