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Generation of three equal-intensity foci based on a modified composite zone plate

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ABSTRACT

In this paper a modified composite zone plate (MCZP) based on the Thue-Morse and Fresnel zone plates is proposed. The focusing properties of the MCZPs are studied theoretically and experimentally. Along the propagation direction the MCZP generates three main foci with approximately equal intensity. The point spread functions (PSFs) at the separate focal planes of the three foci have almost the same ratio between the energy in the diffraction limit region of the PSF plane and the energy in the entire PSF plane. The MCZPs have potential applications in the fields of three-dimensional optical tweezers and multi-plane lithography.

1. Introduction

As a special kind of diffractive optical elements [1–3], zone plates (ZPs) consist of two types of rings with different transmittances. Compared with the periodic sequences, fractal sequences with aperiodic structure have unique diffraction property [4]. The ZPs generated by the aperiodic fractal sequences [5] can be used in many fields, such as THz imaging, X-ray microscopy, Ophthalmology, optical data storage, photon sieves and optical trapping [6–8].

Typical aperiodic ZPs include fractal zone plates [5], Fibonacci zone plates [9], Thue-Morse zone plates [10], and so on. These aperiodic ZPs can be generated with the similar construction method and generate a series of self-similar foci along the optic axis. Although fractal zone plate beams possessing multiple foci can be employed to trap multiple particles simultaneously, the trapping forces imposed on the particles are not balanced [11,12]. The Fibonacci zone plate beams have only two main foci with equal intensity [13]. Although the Thue-Morse zone plate beams can trap multiple particles in more than two focal planes simultaneously, only two of the trapping forces exerted by the foci are nearly equal [10]. Fresnel zone plates (FreZPs) with multi-level phases can generate multiple foci of approximately equal intensity, but fabrication of the devices is challenging [14,15]. Composite zone plates (CZPs), such as composite Fresnel zone plates [16], composite fractal zone plates [17] and composite Thue-Morse zone plates [18], are constructed with mixed ZPs of different orders to enhance intensities of the focal spots, but none of the these CZPs can generate three main foci with approximately equal intensity.

We will propose a modified composite zone plate (MCZP) to generate a beam with three main foci of approximately equal intensity along the optic axis. The inner and outer parts of the MCZP consist of a modified Thue-Morse zone plate (MTMZP) [19] and a FreZP, respectively. We will use Matlab simulations to study the focusing properties of the MCZP and

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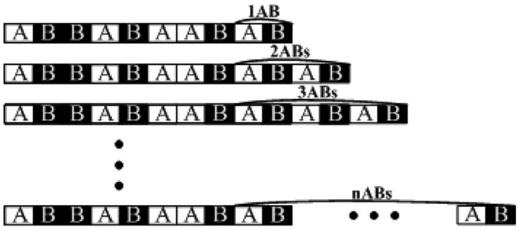

Fig. 1. Schematic of the construction method with the fourth-order MCZP as an example.

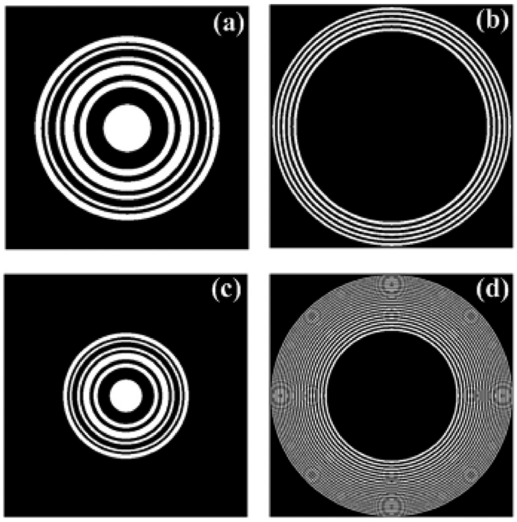

Fig. 2. (a) The inner and (b) outer parts of a MCZP with 5 ABs, respectively. (c) The inner and (d) outer parts of a MCZP with 20 ABs, respectively.

the energy efficiency, which is defined as the ratio of the energy in the diffraction limit region of the point spread function (PSF) plane to the energy in the entire PSF plane. The proposed ZP can be used for three-dimensional (3D) optical tweezers and lithography.

2. Design

Like a ZP, the MCZP consists of alternate transparent (A) and opaque (B) zones. We will use the fourth order MTMZP as an example to describe the design principle of the MCZP. AB represents a pair of cascading transparent and opaque zones and will be used as the duplicate element in the construction of the MCZP. The zone sequence of the MTMZP is expressed as ABBABAABABBABAAB. Fig. 1 shows the MCZPs with n ABs added to the end of the sequence of the fourth order MTMZP. n is a positive integer and represents the number of the added ABs. We will use an empirical method to find the optimal n for a MCZP.

A ZP can be generated with a transmission function [10]. There are 2^S zones in the S-th order, and the transmittances of the zones are 1 or 0, representing with “A” or “B”, respectively. For a conventional composite ZP, the inner and outer parts are of the same ZP, and the size of the inner part is half of the ZP. However, the inner and outer parts of the proposed MCZP are different types of ZPs, and the size of the inner part is not limited by the full size of the ZP. The inner part of the MCZP can be also an arbitrary-order MTMZP. The outer part of the MCZP is the addition of n pairs of ABs. Fig. 2(a) and (b) show the inner and outer parts of a MCZP with 5 ABs, respectively. Fig. 2(c) and (d) show the inner and outer parts of a MCZP with 20 ABs, respectively. The sizes for all the ZPs in Fig. 2 are 512×512 pixels with a pixel area of $15\,\mu m \times 15\,\mu m$. When n is greater, the size of the outer part of a MCZP is larger, but the size of the inner part is smaller.

We use Fresnel diffraction integral to calculate the axial intensity distribution of the ZPs. Fig. 3 shows the corresponding normalized axial intensity distributions for the MCZPs with different ABs. In Fig. 3, the horizontal axis is the reduced axial coordinate u, where $u = a^2/(2\lambda z)$. a, λ and z are the radius of the ZP, the wavelength of light and the axial distance from the ZP, respectively. The vertical axis is the normalized axial irradiance I. From Fig. 3 it can be found that, as long as n ABs are added to the sequence of the fourth-order MTMZP, the modified ZP will generate three foci along the optic axis. When n is different, the intensity non-uniformity of the three main foci is varying. The intensity non-uniformity is defined as