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An arbitrarily designed main focus with high intensity generated by a composite fractional fractal zone plate

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ABSTRACT

In this paper a composite fractional fractal zone plate (CFFZP) based on the corresponding fractional fractal zone plate is proposed to enhance the intensity of the arbitrarily designed main focus. The construction method of the CFFZP has been illustrated in the simulation. It has been also proved in the simulations and experiments that the CFFZP generates the main focus with higher intensity. The proposed zone plate can be applied to stably trap a particle at an arbitrary plane and generate a clearer image at an arbitrary axial position.

1. Introduction

The high-intensity foci with arbitrary positions generated by aperiodic zone plates have many applications [1–5]. The arbitrary foci with high intensities can be used to lithograph easily [6], stably trap particles [7,8] and obtain clearer images at arbitrary planes [9,10].

Aperiodic zone plates can generate special foci. For example, fractal zone plates generate the main foci with a few subsidiary foci, which can be applied to trap multiple particles and reduce the chromatic aberration of images [11,12]; Fibonacci zone plates generate twin foci with equal intensity located at the positions with the golden mean [13–15]; Thue–Morse zone plates generate twin main foci with equal intensity and a few subsidiary foci, which can be applied to trap particles and generate optical images in different planes [16]; an m-bonacci zone plate generates twin foci located at the positions related to the m-golden mean [17,18]. However, the foci generated by these zone plates have low intensities and the focal positions cannot be arbitrarily designed. Some zone plates can generate foci with high intensities. For example, composite Fresnel zone plates [19], composite fractal zone plates [20] and composite Thue–Morse zone plates [7] can enhance the intensities of the foci generated by the corresponding zone plates. Fibonacci lenses with gradient phases can generate twin foci with high intensities [21]. Nevertheless, the axial positions of these high-intensity foci cannot be arbitrarily designed. Some zone plates can generate customized foci. For example, fractional fractal zone plates (FFZPs) can generate the main foci with the arbitrary position [22–24], and a modified Thue–Morse zone plate can generate two designed main foci with a fixed ratio of focal lengths [25]. However, these arbitrarily designed main foci have low intensities and few subsidiary foci.

In this paper a composite fractional fractal zone plate (CFFZP) will be proposed to enhance the intensity of the arbitrarily designed main focus. The proposed zone plate can generate a higher-intensity main focus with many subsidiary foci. The inner and outer parts of the CFFZP are two different FFZPs which both generate the main foci located at the same axial position. The construction method and focusing property of the CFFZP will be illustrated in detail and studied with simulations, respectively. It will be also proved in the experiments that the CFFZP generates the main focus with higher intensity.

2. Design

The focal length f for an FFZP and a fractal zone plate can be calculated in Eq. (1) [22],

$$f(a,\lambda,N,S) = a^2 \cdot \left[\lambda \cdot (2N-1)^S\right]^{-1}, \tag{1}$$

where a is the radius of the outermost ring of the ZP, λ is the wavelength of the incident light, N is an integer or fraction, and the fractal stage S is an integer. In the design, the wavelength is set as a constant. Therefore, the position of the main focus is related to the three variants a, N and S. The phase-only ZP can be obtained with the transmittance function [11]. Compared with an amplitude-only ZP, the phase-only ZP

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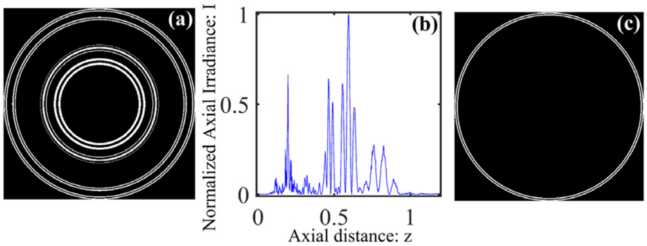

Fig. 1. (a) The phase-only hologram and (b) the axial irradiance of the FFZP of (N = 2.3, S = 3). (c) The outer part of the corresponding CFFZP.

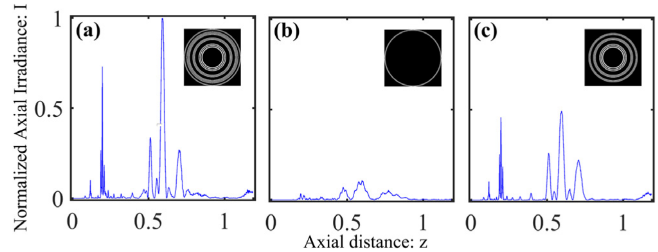

Fig. 2. The axial intensity distributions generated by (a) the CFFZP based on the FFZP of (N = 2.3, S = 3), (b) the outer part of the CFFZP, and (c) the inner part of the CFFZP, respectively. The ZPs are shown as insets.

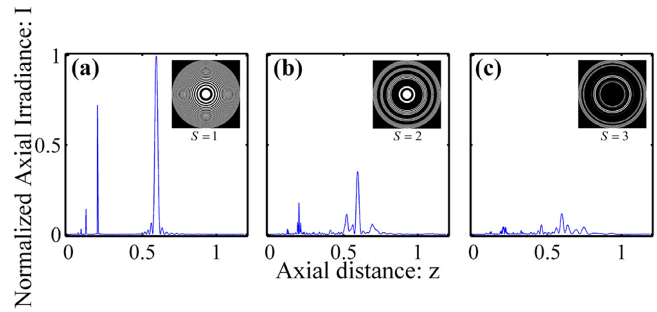

Fig. 3. (a–c) The axial intensity distributions of the CFFZPs with the inner parts based on the FFZPs of S = 1, S = 2, and S = 3, respectively. The ZPs are shown as insets.

has higher diffraction efficiency and will be applied in this paper [11]. The angular plane-wave spectrum theory will be used to analyze the focusing properties of the CFFZPs [11].

A CFFZP consists of different FFZPs which generate the main foci with the same focal length. Firstly, we will explain the construction method for the outer part of the CFFZP in detail. In the simulation, the parameters are set as follows, the sampling points $Nx = Ny = 512$, wavelength λ = 532 nm, pitch = 15 μm, and the length (equal to width) of the spatial light modulator (SLM) L = 512 × pitch. Fig. 1(a) shows a phase-only FFZP of (N = 2.3, S = 3). Fig. 1(b) shows the axial irradiance generated by the FFZP. z is the axial distance between the ZP and the measured position. It can be seen in Fig. 1(b) that the FFZP generates a main focus with a focal length f = 594.1 mm calculated from Eq. (1). Fig. 1(c) shows the three outermost rings of the FFZP of (N = 2.3, S = 3), which are also the outer part of the corresponding CFFZP. In fact, the outer part of a CFFZP is the three outermost rings of a corresponding FFZP, so the intensity of the main focus is enhanced. In this paper the three outermost rings of the FFZP are chosen as the outer part of the corresponding CFFZP, and the remaining part of the CFFZP, i.e., the inner part of the CFFZP, has a larger area. The fractal property of the three outermost rings conforms that of the cantor sequence. The radius of the inner part in Fig. 1(c) is 248 × pitch. For receiving more light, the inner part of the CFFZP is preferred to be larger.

Next, we will introduce the construction method for the inner part of the CFFZP. As an example, firstly, we set the radius of the inner part of the CFFZP as 248 × pitch and the fractal stage S as 2. Use the parameters λ, S and f to calculate the corresponding N with Eq. (1), determine the phase diagram for the inner part of the CFFZP with the radial size, S and N, combine the phase diagrams of the inner and outer parts of the CFFZP, and calculate the axial intensity distribution of the CFFZP. Then decrease the original radial size of the inner part of the CFFZP one pixel by one pixel, and calculate the corresponding axial intensity distribution again. Finally, the main focus with the highest intensity for the CFFZP is obtained and the radial size is optimized for the inner part of the CFFZP. When the radial size of the inner part of the CFFZP based on the FFZP of (N = 2.3, S = 3) is set as 245 × pitch, the intensity of the main focus is the strongest. On the basis of Eq. (1), the inner part of the CFFZP can be regarded as an FFZP of (N = 3.7684, S = 2). It should be noted that although the inner and outer parts of a CFFZP generate the main foci located at the same position, the size of the inner part would affect the intensity of the designed main focus. The main reason is that the size of the boundary region between the innermost ring and the outermost ring affects the optical path difference for the light reaching the designed focus.

Then we will analyze why a CFFZP can generate a main focus with high intensity. Fig. 2(a–c) show the axial intensity distributions of the CFFZP based on the FFZP of (N = 2.3, S = 3), the outer part of the CFFZP, and the inner part of the CFFZP, respectively. The two-dimensional structural patterns of the ZPs are correspondingly shown as insets in the upper right corners of the images. The sizes for all the ZPs in Fig. 2 are 512 × 512 pixels with a pixel area of 15 μm × 15 μm. It should be noted that the CFFZP in Fig. 2(a) generates the main focus with the highest intensity. In Fig. 2(b) the intensity of the main focus in the first-order focal region generated by the outer part of the CFFZP is the lowest. The main reason is that there are only a few rings in the phase diagram. As a CFFZP comprises two FFZPs with the same center, the beams generated by the two parts propagate coaxially. Moreover, the two FFZPs generate the main foci at the same position. Thus, the CFFZP can generate a single main focus with higher intensity.

We will analyze the influence of the fractal stage S of the inner part of a CFFZP on the axial intensity distribution. In the following, the outer part of the CFFZP comprises the three outermost rings of the FFZP of (N = 2.3, S = 3), and the inner part of the CFFZP comprises an FFZP with a different S. The CFFZPs in Fig. 3(a–c) are combined with the outer part and one of the inner parts of the FFZPs of (N = 21.866, S = 1), (N = 3.7684, S = 2) and (N = 2.2433, S = 3) with the radial sizes of 245 × pitch, 245 × pitch and 244 × pitch, respectively. The ZPs are shown as insets in Fig. 3. When the fractal stage S of the inner part of the CFFZP is 1, like a Fresnel zone plate, the corresponding CFFZP in Fig. 3(a) generates a single main focus with the highest intensity but fewer subsidiary foci. Compared with the CFFZP in Fig. 3(c), the CFFZP in Fig. 3(b) generates a main focus with higher intensity and almost the same number of the subsidiary foci. Therefore, the CFFZP with the inner part of the FFZP of S = 2 can generate the required axial irradiance.

Finally, we will illustrate the design of a CFFZP with an arbitrary size. The CFFZP based on the FFZP of (N = 2.3, S = 3) is chosen as an example for the illustration. Although the size of the ZP in the simulation is 512 × 512 pixels with a pixel area of 15 μm × 15 μm, we can design a CFFZP with any given size. Note that in Eq. (1) the ratio between a^2 of any two FFZPs with the same fraction N and fractal stage S is equal to the ratio of the two corresponding focal lengths. In fact, this feature of the FFZPs applies to those of the CFFZPs, too. A CFFZP with a desired size can be generated according to the following steps. Firstly, calculate the ratio between the sizes of the expected CFFZP and a grid of 512 × 512 pixels. Secondly, N and S for the inner and outer FFZPs of the expected CFFZP are the same as those for the CFFZP with 512 × 512 pixels, and the multiplication of a^2 for the CFFZP with 512 × 512 pixels and