Optics Communications 413 (2018) 44–47

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

An amplitude and phase hybrid modulation Fresnel diffractive optical element

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ARTICLE INFO

Keywords:
Diffraction
Fresnel zone plate
Fresnel lens
Hybrid modulation

ABSTRACT

An Amplitude and Phase Hybrid Modulation Fresnel Diffractive Optical Element (APHMFDOE) is proposed here. We have studied the theory of APHMFDOE and simulated the focusing properties of it along the optical axis, which show that the focus can be blazed to other positions with changing the quadratic phase factor. Moreover, we design a Composite Fresnel Diffraction Optical Element (CFDOE) based on the characteristics of APHMFDOE. It greatly increases the outermost zone width without changing the F-number, which brings a lot of benefits to the design and processing of diffraction device. More importantly, the diffraction efficiency of the CFDOE is almost unchanged compared with AFZP at the same focus.

1. Introduction

The Fresnel diffractive optical elements are generally classified into amplitude and phase type according to the modulation mode to incident light. Amplitude Fresnel diffractive optical element is often referred to as Amplitude Fresnel Zone Plate (AFZP). It is actually a circular diffraction grating that focus the incident light to a series of foci along the optical axis and therefore divides the energy into different foci. The diffraction efficiency decreases with the increase of absolute value of the diffraction order [1]. Phase Fresnel diffraction optical element mainly include Phase Fresnel Zone Plate (PFZP) [2], Fresnel lens [3]. These elements can modulate the energy of the incident light so that they could have greater diffraction efficiency than AFZP.

In this paper, we will present an Amplitude and Phase Hybrid Modulation Fresnel diffraction optical element (APHMFDOE). It is generated by adding a diffraction phase profile to the transparent band of the AFZP. The periodic distribution of amplitudes ensures the regular distribution of a series of foci along the optical axis, while the phase profile is used to modulate the incident so that the maximum diffraction efficiency can be achieved at the desired position. Furthermore, when the primary focal length is reduced by this way, the F-number is reduced as well. However, the width of each zone does not decrease, which is equivalent to increasing the width of each zone. In some applications of Fresnel diffractive optical elements with large numerical aperture, for example the Fresnel Corrector in the Schupmann system [4], APHMFDOE can help to increase the design flexibility and machinability of the Fresnel device to some extent.

2. The theory and simulation of APHMFDOE

2.1. Theory derivation

As the structure of the AFZP is rotationally symmetric, the Fourier series of the transmittance function of the AFZP g(r) can be written as follows (see Appendix):

$$g(r) = \sum_{m=-\infty}^{+\infty} g_m(r) \tag{1}$$

where

$$g_m(r) = \begin{cases} \frac{1}{2} & m = 0 \\ 0 & m\ is\ even,\ \mathrm{m} \neq 0 \\ \frac{i}{m\pi} \exp\left[i \frac{k}{2[f/m]} r^2\right] & m\ is\ odd \end{cases} \tag{2}$$

When the AFZP is perpendicularly illuminated by a plane wave with unit amplitude, a series of light spot is aligned along the optical axis at $f, f/3, f/5, \ldots, f/m$ positions, where m is an odd number. In analogy to blazed grating, which is generated on the basis of grating by adding a linear phase factor to it [5], APHMFDOE is generated by adding a quadratic phase factor $\exp\left(ipkr^2/2f\right)$ to $g(r)$, p is a real number which is used to regulate the phase factor. Therefore one can obtain the transmittance function of the APHMFDOE $g'(r)$ as follows:

$$g'(r) = \sum_{m=-\infty}^{+\infty} g'_m(r) \tag{3}$$

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https://doi.org/10.1016/j.optcom.2017.12.023
Received 3 October 2017; Received in revised form 1 December 2017; Accepted 10 December 2017
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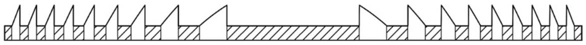

Fig. 1. The surface type of APHMFDOE.

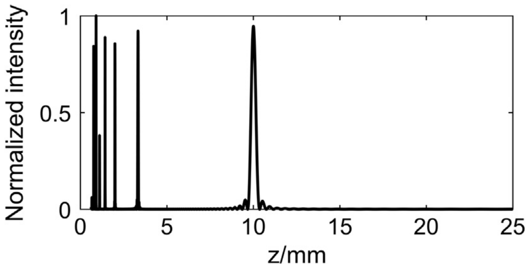

Fig. 2. The normalized axial intensity distribution of AFZP.

where

$$g'_m(r) = \begin{cases} \frac{1}{2} exp\left(i\frac{k}{2f/p}r^2\right) & m = 0 \\ 0 & m\ is\ even,\ \mathrm{m} \neq 0 \\ \frac{i}{m\pi}\exp\left[i\frac{k}{2\left[f/(m+p)\right]}r^2\right] & m\ is\ odd \end{cases} \tag{4}$$

From the Eq. (4), we know that the focus of the mth order diffraction light is moved from the position of f/m to $f/(m+p)$. In addition, zero-order light is introduced to focus at the f/p position. For a more intuitive understanding of APHMFDOE, we draw a diagram of the surface type of APHMFDOE in Fig. 1, in which the shaded part is opaque. The height of the phase profile is related to the quadratic phase factor and refractive index of the material. The detailed surface type will be discussed in the following contents.

2.2. Comparison of simulation results of APHMFDOE and AFZP

Consider an AFZP with diameter of 1.2 mm and focal length of 10 mm at wavelength of 632.8 nm, which is perpendicularly illuminated by a plane wave with unit amplitude. From the Fresnel diffraction integral formula, the corresponding diffracted field $U(z)$ along the optical axis can be expressed as [6]:

$$U(z) = \frac{k}{iz}\exp(ikz)\int_0^R \mathrm{g}(r)\exp\left(\frac{ikr^2}{2z}\right) r dr \tag{5}$$

where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, i is the imaginary unit. Based on the Eq. (5), one can obtain the normalized light intensity distribution along the optical axis which is showed in Fig. 2.

To observe the modulation effect to the energy of the incident light by APHMFDOE, two different quadratic phase factors with different values of p are added to AFZP. After that, two different APHMFDOEs are obtained so as to compare with the AFZP mentioned above. When they are perpendicularly illuminated by plane waves with unit amplitude, the energy is redistributed along the optical axis showed in Fig. 3.

From the above figures, one can obtain that the simulation results are in good agreement with the theoretical formulas. First, it is clear to see that APHMFDOE can change the intensity distribution of light on the axis compared with the result in Fig. 2. Second, the foci are moved to different positions when p takes different value, and the moving distance is related to the value of p. For example, tracking 1th-order diffraction light, we can find that the corresponding focus is shifted to the left with different distances in Fig. 3. That is to say the focal length can be changed to the desired value when choosing the appropriate value of p. More importantly, the distribution of Fresnel zone width does not change in the process of focal length change.

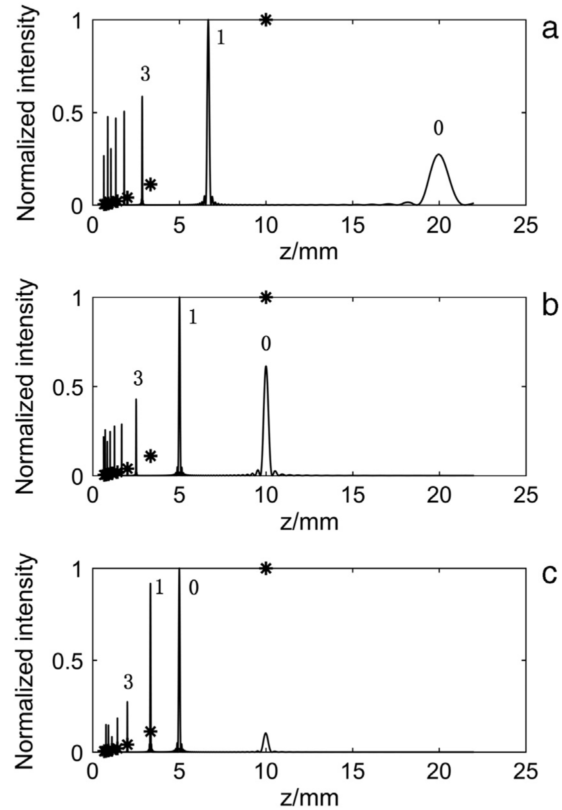

Fig. 3. The axial intensity distribution of APHMFDOEs with different value of p. The values of p are (a) $p = -0.5$, (b) $p = -1$ and (c) $p = -2$. The symbol '*' indicates the theory position of AFZP's diffraction focus, while the numbers 0, 1 and 3 indicate the position of zero-order, 1th-order and 3th-order diffraction light.

From the above theory, it seems that we can modulate the main focus to any position if we choose an appropriate value of p. However, we have to add some restrictions to the phase component to ensure the reliability of the theory and the machinability of the APHMFDOE. In terms of the reliability of the above theory, some constraints must be added to the value of p to ensure the applicability and reliability of the paraxial diffraction theory. First, we introduce the Fresnel number showed in Eq. (6) [7].

$$F = \frac{R^2}{\lambda z} \tag{6}$$

where R is the radius of APHMFDOE, z is the distance from the observation surface to APHMFDOE. In general, the Fresnel approximation works well when $F > 1$ [7]. For the mth diffraction order, the distance z is $|f/(m+p)|$. Substituting z and the constraint of F into Eq. (6), one can obtain

$$|m+p| > \frac{\lambda f}{R^2} \tag{7}$$

So the p in the phase must first satisfy the Eq. (7).

In terms of machinability of the APHMFDOE, the phase component makes the APHMFDOE more complicated for processing. In order to make the APHMFDOE easier to process, we must first ensure that the profiles of the phase component must be continuous in a transparent band. This can be satisfied as long as the maximum phase shift in a transparent band is equal to $n\pi$ or $2\pi/n$, n is a positive integer. For the added phase factor $\exp\left(ipkr^2/2f\right)$, that is to say, the value of p or $2/p$ in it must be an integer. In order to understand the above conditions more clearly, we have drawn the surface types of different APHMFDOE with different values of p in Fig. 4. However, we find that the APHMFDOE introduces the thin-walled structure when $-1 < p < 0$, which is difficult to process. On the contrary, when $p < -1$, the surface type of the