Optik - International Journal for Light and Electron Optics 174 (2018) 387–393

Contents lists available at ScienceDirect

Optik

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

Original research article

Toward binary Gabor zone plate by modulating zones width

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ARTICLE INFO

Keywords:
Gabor zone plate
Single focus diffraction
X-ray diffraction

ABSTRACT

In this paper, a novel concept of modulated width zone plate (MWZP) is proposed to realize a binary Gabor zone plate (GZP) with single focus. By modulating the zones width as sinusoidal random distribution, higher-order foci can be effectively suppressed. The physical design is verified with numerical simulation and demonstration experiments in visible light region. The performance of the modulated width zone plate is determined by the number of zones used. It works well only when enough zones are utilized. The zone plate is easy to be fabricated employing nanofabrication technology, since it is composed of complete zones, similar to Fresnel zone plates (FZP). This work offers new opportunities for x-ray spectroscopy and microscopy in physics research.

1. Introduction

Since Rayleigh invented Fresnel zone plate in 1871, it is widely used in microscopy and spectroscopy of extreme ultraviolet, X-ray radiation [1–3], and in focusing of neutral atom or molecular beams [4,5]. It is not usually used in visible light region since traditional refractive lens supply better capabilities. Fresnel zone plate consists of alternating opaque and transparent concentric circular zones and the transmittance function of Fresnel zone plate is a binary stair-like function. The achievable spatial resolution of Fresnel zone plate is related to the width of the outermost zone, which is limited by today's nanofabrication technology. It is reported that a resolution of 12 nm has been achieved by Chao et al. [6] using the full field soft X-ray microscope. Fresnel zone plate has multi-order diffraction foci, among which the 1st order focus is of most important. The critical defect of ordinary Fresnel zone plate is the additional background noise contributed by multi-order foci.

Gabor zone plate [7,8] could suppress all high order foci and has only a virtual and a real focus as a consequence of its sinusoidal continuous varying transmittance function along the radial direction. The Gabor zone plate for visible light could be achieved by optical methods, for example, the hologram produced by a plane wave shining on a single elastic point scatterer could act as a Gabor zone plate [9]. Though it is attractive, no Gabor zone plate has been found to be used in focusing X-ray or other areas, owing to the technological impossible to meet the demand of sinusoidal transmittance function for X-ray.

Many methods have been attempted to approach Gabor zone plate [10–23]. Tatchyn et al. [10] have realized Gabor zone plate through controlling the thickness of zone plate. In the design, the thickness of the zone plate is a function of radius. Patt et al. [11] have done a similar work and fabricated a Gabor zone plate with eight zones and a diameter of 3 mm. However, the three-dimensional complex structures in the patterns and the nonlinear response of the medium limit their use.

Beynon et al. [12–14] have suggested to produce Gabor zone plate in a binary form (BGZP) by using a radial and an azimuthal

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https://doi.org/10.1016/j.ijleo.2018.08.089
Received 20 January 2018; Received in revised form 24 July 2018; Accepted 23 August 2018

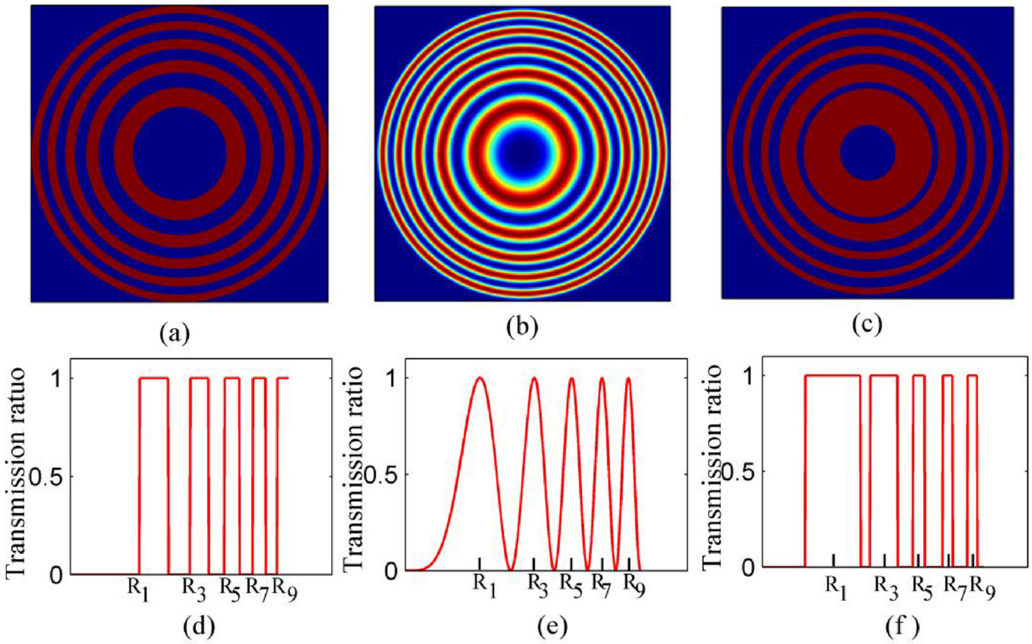

Fig. 1. The contrast of Fresnel zone plate, Gabor zone plate and the modulated width zone plate. (a) A Fresnel zone plate with 5 zone pairs. (b) A Gabor zone plate with 5 zone pairs. (c) A modulated width zone plate with 5 zone pairs. (d) The transmittance curve of Fresnel zone plate plotted against its radius. (e) The transmittance curve of Gabor zone plate plotted against its radius. (f) The transmittance curve of modulated width zone plate plotted against its radius.

variation transmittance function. The binary Gabor zone plate only has opaque or transparent regions, which makes it easier to fabricate. Later, Choy et al. [15] have developed a new model to approximate the binary Gabor zone plate and gained higher efficiency. Kipp et al. [17] have introduced an ingenious Photon Sieve to focus sharper image, which is suggested to be taken to space [18]. Recently, some novel configurations of binary Gabor zone plate have been proposed to decrease the manufacture difficulty, including Annulus-sector-element coded Gabor zone plate (ASZP) [19], Quasi-random-dot-array binary Gabor zone plate (QBGZP) [20] and Stagger arrangement zone plate (SZP) [21]. The fabrication is still challenging for these configurations because of the existing micro structures and complex transmission curves in those configurations.

In this paper, we propose a novel single focus zone plate by modulating the zone width as sinusoidal random distribution to realize a Gabor zone plate. The modulated width zone plate shows outstanding property of single focus when enough zones are illuminated. The modulated width zone plate consists of a series of alternating transparent rings and opaque rings without complex curve, micro or sharp structures, which is different from other binary Gabor zone plates referred above. Thus, compared to Fresnel zone plate, the fabrication of the modulated width zone plate does not increase difficulty. In the following passage, the physics design, numerical simulation and experiments results of the modulated width zone plate will be introduced in details, along with some discussions on its characteristics.

2. Design of the MWZP

Fresnel zone plate consists of alternating opaque and transparent concentric annular rings as showed in Fig. 1(a). It is well known that the radius of the n^{th} zone is

$$R_n = \sqrt{nf\lambda + (\frac{n\lambda}{2})^2}, \tag{1}$$

where λ is the wavelength of light, and f represents for the first order focal length of the zone plate. In general, the second term in the equation could be ignored since we always have $f \gg n\lambda$. Therefore the radius of the n^{th} zone can be written as $\sqrt{n\lambda f}$. Obviously, all the zones are of constant area equal to $\pi\lambda f$.

The transmittance function of Fresnel zone plate is a binary stair-like function as illustrated in Fig. 1(d), which is plotted against its radius. And it can be expressed in the following form:

$$t_F(r) = \begin{cases} 0, \ 2n\lambda f \le r^2 < (2n+1)\lambda f \\ 1, \ (2n+1)\lambda f \le r^2 < (2n+2)\lambda f \end{cases}, \ n = 0, 1, 2, 3, \cdots \tag{2}$$

Gabor zone plate is similar to Fresnel zone plate, comprises concentric rings of equal area, showed in Fig. 1(b). The difference is