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Generation of double line focus and 1D non-diffractive beams using phase shifted linear Fresnel zone plate

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A B S T R A C T

Phase shifted linear Fresnel zone plates are presented for the first time. These diffractive elements are linear Fresnel zone plates in which their phase are laterally shifted. The impact of the phase shifting on their diffractive and focusing properties are studied. It is demonstrated that by shifting the phase, two parallel linear beams can be generated at the focal plane. Furthermore, as they are propagating, a non-diffractive line-shaped beam is generated at a given distance from the focus. Transverse intensity profile of the beam at different distances as well as its cross section of propagation along the optical axis clearly shows that the intensity profile of the beam is really kept unchanged as it is propagated. All results are completely verified by experiments.

1. Introduction

Zone plates are optical elements which focus light by diffraction instead of refraction as in conventional lenses. A Fresnel-type zone plate has many concentric circular regions which are alternately opaque and transparent. The widths and radii of the zones are such that light diffracted from the center of every transparent region reaches a focal point on the axis of the plate in phase. The result is constructive interference, and the creation of a bright spot. Such Fresnel zone plates also have high order diffraction focuses along the beam axis, which occur when the phase shift from adjacent transparent regions is an integer multiple of 2π.

Linear Fresnel zone plate (LFZP) has one-dimensional Fresnel zones and acts like cylindrical lenses to create line focus [1]. Therefore, this element serves as a diffractive cylindrical. There are numerous practical examples where waves are focused by a cylindrical lens. Some recent important examples include plasmonics, light-sheet microcopy [2–5], line illumination microscopy [6–8], and the cubic phase mask for depth-of-focus enhancement [9]. These are in addition to other more established areas including particle velocimetry, integrated optics, and planar optics.

Recently, we introduced a phase shifted Fresnel zone plate to generate annular focus as well as non-diffractive bessel beam [10]. Concerning the idea, we are about to introduce a novel and interesting application of LFZP, besides the above-mentioned examples. To the best of our knowledge, we implemented LFZP as a double line generator, for the first time. Furthermore, we showed that it may be used to create a 1D non-diffractive beam generator.

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2. Mathematical formalism

A classic Fresnel zone plate (FZP) is a combination of alternative annular transparent and opaque zones. The annular rings are designed such that the optical path lengths for the light deflected from adjacent zones towards a common focal point differ by integral multiples of wavelength. Considering above-mentioned diffractive properties of FZP, a linear FZP may be defined in which circular zones are replaced by parallel straight zones. If x_n and f denote coordinates of the center of n-th linear zone and the focal length, respectively. This condition is mathematically expressed as $x_n^2+f^2=(f+n\lambda/2)^2$. For the paraxial approximation, where $f \gg n_{max}\lambda$, we can approximate $x_n=\sqrt{nf\lambda}$. This condition describes structure of LFZP which is periodic in x^2 with period x_1^2. Considering phase structure, the element has a line-focus that acts as a cylindrical lens, so its focal length is determined by $f=x_1^2/2\lambda$. Phase distribution across the FZP is given by $\phi(x)=-(2\pi/\lambda)(x^2/2f)$. Now, if the phase is laterally shifted, for example by αL, PS-LFZP is constructed. In which $2L$ and α are width of the LFZP and the shift controller, respectively. Expression for the phase shift may be given by

$$\phi(x)=-\frac{2\pi}{\lambda}\frac{(x\pm\alpha L)^2}{2f}, \quad -1<\alpha<1. \tag{1}$$

Positive and negative shifts (or sign of α) are correspondence to negative and positive x, respectively. Let us look further into its phase structure to better realize diffractive properties of the phase shifted linear FZP (PS-LFZP). Typical LFZP and PS-LFZP as well as their phase profile were shown in Fig. 1(a) through (d). As it is shown that the minimum phase of the PS-LFZP is located at the distance αL around the center of the LFZP. To ensure focusing properties of these elements

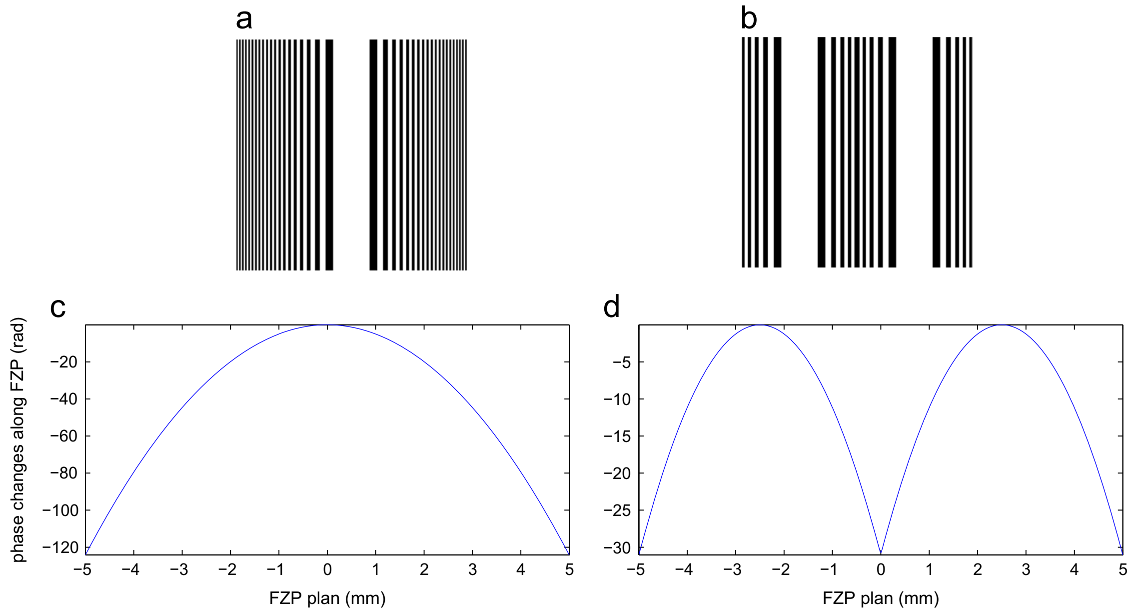

Fig. 1. Typical patterns of (a) LFZP and (b) PS-LFZP, upper figured as well as (c) phase profile of LFZP and (d) PS-LFZP, lower ones.

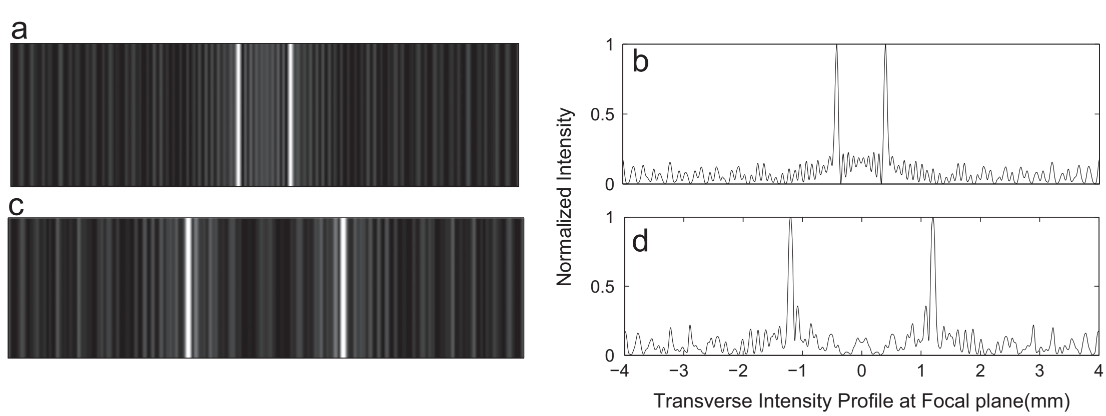

Fig. 2. The effect of different α on the focused double lines. (a, b) $\alpha=0.1$ and (c, d) $\alpha=0.3$. Left figures: intensity distributions and the right ones: corresponding intensity profiles.

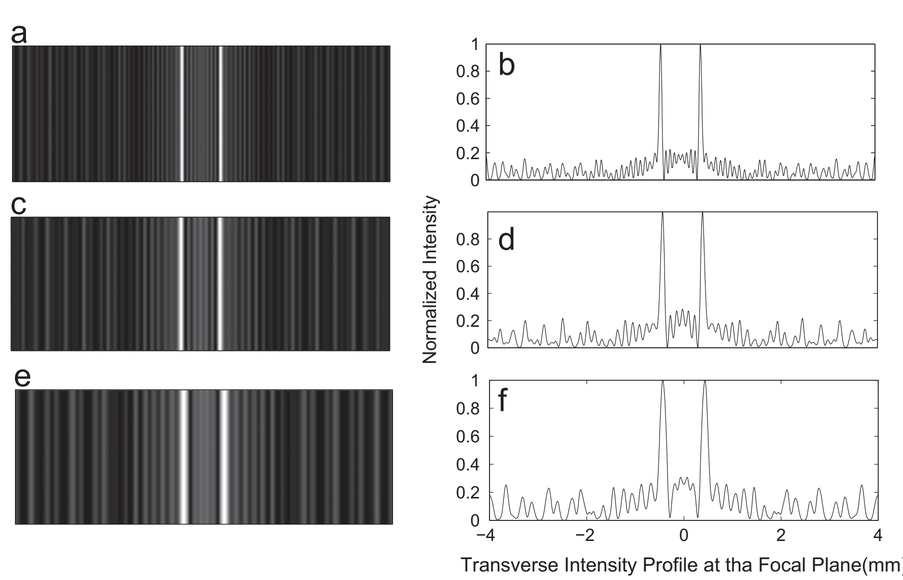

Fig. 3. The effect of different focal lengths (a, b) 500, (c, d) 750 and (e, f) 1000 mm on the focused double lines. Left figures: intensity distributions and the right ones: corresponding intensity profiles.