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Two high-intensity foci with the generalized mean generated by a kinoform generalized mean lens

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ABSTRACT

A kinoform generalized mean lens (KGML) is proposed to generate two high-intensity foci with the generalized mean. The construction method of a KGML has been illustrated in the simulation. It has been proved in the simulation and experiment that a KGML generates twin foci with high intensity and the generalized mean. Moreover, the self-reconstruction property of the KGML beam is verified with numerical simulations. The proposed zone plate can be applied to trap two particles stably and generate two clearer images at two different axial positions being the generalized mean.

1. Introduction

High-intensity foci have many applications in the different fields [1–4]. High-intensity foci generated by a devil's lens [5] and composite Thue-Morse zone plate [6] can be applied to reduce the chromatic aberration of an image [7] and stably trap particles at the multiple planes simultaneously [8–10], respectively.

Some zone plates can generate twin foci. Thue-Morse zone plates generate twin foci with a few subsidiary foci [11]. Fibonacci zone plates can generate twin foci with the golden mean applied to generate double vortices [12,13]. A generalized Fibonacci zone plate generates twin foci located at the positions being different ratios [14]. A three-dimensional-printed THz diffractive lens generates two THz images with the golden mean [15]. A m-bonacci zone plate generates twin foci located at the positions related to the m-golden mean [16,17]. A generalized mean zone plate (GMZP) can generate twin foci with the generalized mean [18]. Nevertheless, twin foci for the above devices have not high intensities. Some special methods are proposed to enhance the intensities of foci generated by zone plates. Kinoform Fibonacci lenses generate two high-intensity foci located at the positions being the golden mean [19]. Devil's lenses with gradient phases [20,21], and composite zone plates, for example, composite fractal [22] and Thue-Morse zone plates [6], can generate the high-intensity foci. A modified Thue-Morse zone plate with the modified structure and optical path difference method can generate two high-intensity foci located at the position being the define ratio [23,24]. However, the ratios of the positions for the above high-intensity foci are not the generalized mean.

In this paper, we propose a kinoform generalized mean lens (KGML) to enhance the intensities of twin foci generated by a GMZP. Compared with the GMZP, the proposed lens can generate the high-intensity twin foci with the generalized mean. We will illustrate in detail the design of the KGML. It will be proved in the simulation and experiment that the KGML can generate twin foci with high intensity.

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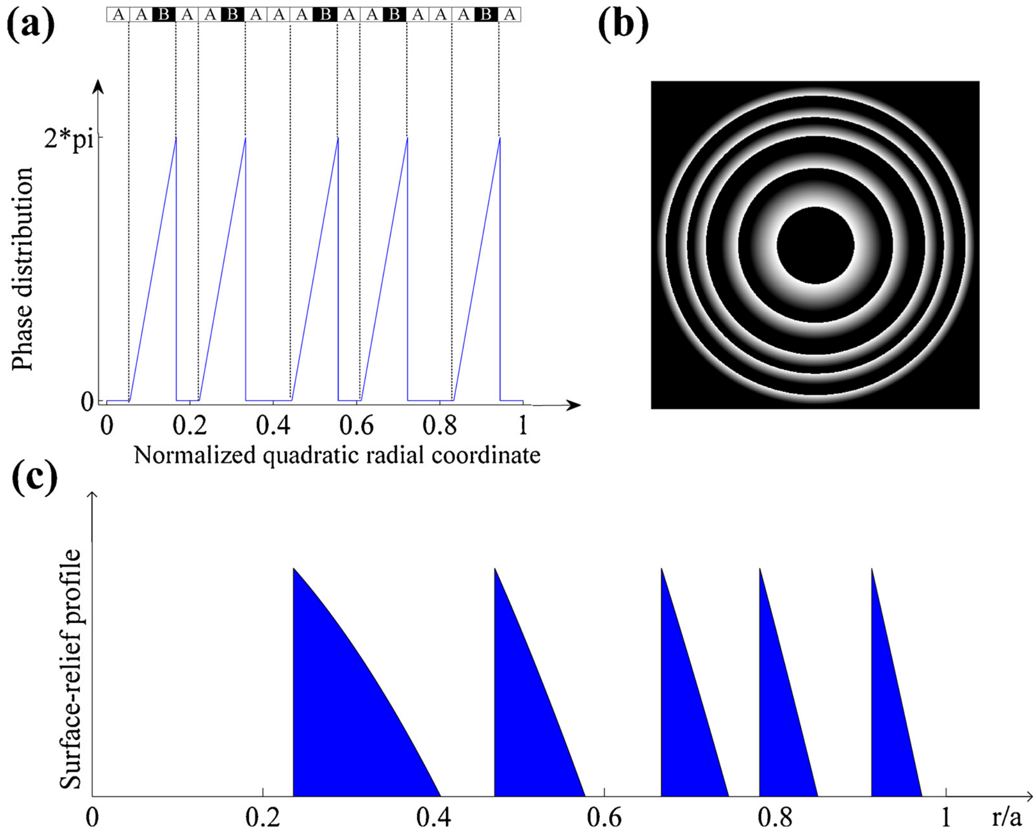

Fig. 1. (a) The phase profile against the normalized quadratic radial coordinate for the KGML of ($S = 3$, $m = 3$, $C = 2$), (b) phase diagram and (c) surface-relief profile of the KGML of ($S = 3$, $m = 3$, $C = 2$).

2. Design

The KGML of order S can be designed by the phase distribution function $F_S(\zeta)$ of the KGML, where $\zeta = (r/a)^2$ is the normalized quadratic radial coordinate and a is the lens radius. Fig. 1(a–c) show the phase profile against the normalized quadratic radial coordinate for the KGML of ($S = 3$, $m = 3$, $C = 2$), phase diagram and surface-relief profile of the KGML of ($S = 3$, $m = 3$, $C = 2$), respectively. $F_S(\zeta)$ shown in Fig. 1(a) is defined with a linear variation between 0 and 2π at each subinterval {AB} of the sequence for the KGML of ($S = 3$, $m = 3$, $C = 2$), being 0 otherwise, and can be calculated in Eq. (1).

$$F_S(\zeta) = \begin{cases} 2\pi\cdot\left(\zeta - \frac{m-1}{k}\right)/\left(\frac{n}{k} - \frac{m-1}{k}\right) & \frac{m-1}{k} \le \zeta \le \frac{n}{k}, \\ 0 & others \end{cases} \tag{1}$$

where k is the number of elements of the sequence for the KGML of order S. m and n are the ordinal numbers of two elements A and B for each subinterval {AB} of the corresponding sequence, respectively. It should be noted that both the KGML and GMZP of order S can be constructed by the generalized mean sequence of order S [18]. The transmittance function $q(\zeta, S)$ of the KGML of order S is defined by

$$q(\zeta, S) = \exp[-iF_S(\zeta)]. \tag{2}$$

The phase profile of a KGML can be acquired by the transmittance function, for example, the phase profile of the KGML of ($S = 3$, $m = 3$, $C = 2$) shown in Fig. 1(b). The surface-relief profile of the KGML of order S is then calculated by

$$\Phi_S = \mathrm{mod}_{2\pi}\{-F_S(\zeta)\}. \tag{3}$$

The surface-relief profile of the KGML of ($S = 3$, $m = 3$, $C = 2$) can be obtained by Eq. (3) in Fig. 1(c).

3. Focusing properties

The angular plane-wave spectrum theory is used to analyze the focusing properties of KGMLs [2]. Fig. 2 from left to right in the first row shows the normalized axial irradiances of the KGMLs of ($S = 3$, $m = 2$, $C = 2$), ($S = 4$, $m = 2$, $C = 2$) and ($S = 5$, $m = 2$, $C = 2$), respectively, and in the second row the normalized axial irradiances of corresponding Fresnel kinoform lenses (FKLs) with the