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Focal shift and focusing properties generation by radial cosine phase masks

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Abstract

Focal shift and focusing properties of Gaussian beams induced by radial cosine phase masks are investigated. Results show that focal shift and the energy distribution among intensity peaks are controlled by two different parameters of the radial cosine phase mask. Increasing the value of frequency parameter in the cosine part of the phase mask, focal shift and focal switch may occur, simultaneously, the focal shift direction may change. Moreover, by altering frequency parameter or phase variation parameter of the phase mask will change the energy distributions of maximum intensity peak and other small intensity peaks. And novel focal patterns also evolve considerably, such as from only one peak to six of multiple peaks. The tunable focal shift can be used to construct controllable optical tweezers. In practice, the tunable phase mask can be implemented through liquid crystal spatial light modulator, which can conveniently alter the wavefront phase distribution of the incident laser beam in the control of computer.

Keywords: Focal shift; Focusing properties; Radial cosine phase mask; Optical tweezers

1. Introduction

Tracing the movement of the point of absolute maximum intensity along the axis has become the subject of a number of publications for several decades [1–10]. It is found that the point of absolute maximum intensity does not coincide with the geometrical focus but shifts along the axis towards the aperture of the optical system [6–8]. More interestingly, the focal shift may be discontinuous in certain optical focusing system. It is found that the focal shift may be accompanied by an effective permutation of the focal point, and this effect is referred to as focal switch [9,10]. The design of phase-only filters has received a great deal of attention due to the fact that phase masks present better performance than intensity transmittance. The use of phase masks for controlling the light intensity distribution near the geometrical focus of an optical focusing system is a topic of great interest in many applications. For example, phase masks can be designed to get axial and transverse superresolution with applications in fields as confocal microscopy [11–13], optical data storage [13,14], astronomy [15], free-space communications [16] and optical tweezers [17–19]. A number of approaches have been proposed to increase the efficiency and speed of optical trapping, for example, the use of a generalized phase-contrast technique [20,21],

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holographic optical tweezers arrays [22]. An interferometer pattern between two annular laser beams was also used to construct three-dimensional trapped structures within an optical tweezers setup [23]. In this paper, we propose an efficient phase mask based on phase-only filters placed on the objective pupil plane. The energy distributions of maximum intensity peak and other small intensity peaks will change by altering frequency parameter or phase variation parameter of the phase mask. Moreover, novel focal pattern also evolves considerably. Increasing the phase variance of frequency parameter may change the move direction of the focal shift. This paper is organized as follows: Section 2 shows the principle of focusing optical system, in which Gaussian beam is apodized and the radial cosine phase mask is introduced. Section 3 presents results and discussions. Conclusions are summarized in Section 4.

2. Principle of the focusing system

In the focusing system we investigate, a circular phase mask can change the phase of an incident beam with radial cosine distribution in the transverse plane, the phase mask is placed in front of the aperture plane of the lens, then the modulated beam with radial cosine distribution is focused through an objective lens, The phase distribution of the beam modulated by the phase mask can be written as

$$\phi = D\pi \cos(C \cdot r \cdot \pi) \tag{1}$$

where C and D are the tunable parameters of the phase mask, C is the frequency parameter in cosine part of the phase mask and it denotes the radial change frequency of the phase and D is a constant number and it denotes variable rate of phase variation. The motive to choose this kind of radial cosine phase masks is that it is very simple and easy to carry out. Gaussian beam is very useful and common beam, so it is chosen as an incident beam here. It is assumed that the waist of Gaussian beam is very close to the lens and the amplitude transmissivity of the phase mask is uniform. The three dimensional amplitude distribution in focal region can be expressed as

$$G(\rho, \mu) = 2\int_0^1 \exp(\mathrm{i}\phi) r \cdot J_0(\rho r) \exp\left[-\left(\frac{1}{w^2} + \frac{1}{2}\mathrm{i}u\right) r^2\right] \mathrm{d}r \tag{2}$$

where $w = \omega_0/a$, ω_0 is the genuine waist width of the Gaussian beam and a is the radius of optical aperture, r is the radial coordinate of the objective lens' pupil plane, ρ and μ are the normalized radial and axial coordinates in focal region, given by

$$\rho = (2\pi/\lambda)(NA)R, \quad u = (2\pi/\lambda)(NA)^2 Z \tag{3}$$

where R and Z are the genuine radial and axial coordinates in focal region. The incident Gaussian beam is considered to study the effect of the phase mask on focal shift and focusing properties.

3. Results and discussions

The optical intensity distribution in focal region is calculated as the squared modulus of amplitude distribution in focal region equation (2). Without losing generality and validity, the intensity is normalized by optical intensity maximum. And the unit of the radial and axial coordinates is $\lambda/2\pi$ in the figures, λ is the wavelength of the incident beam. Fig. 1 illustrates the evolution of three-dimensional light intensity distribution for $D = 1$ with changing parameter C. It can be seen that the three-dimensional distribution of light intensity changes considerably with parameter C. When parameter $C = 1$, there is only one light intensity peak, and the point of maximum light intensity does not coincide with the geometrical focus but shifts along the axis towards the aperture of the optical system, as shown in Fig. 1(a). However, by increasing C to 2, some small light intensity peaks appear beside the maximum light intensity peak near the optical aperture and the

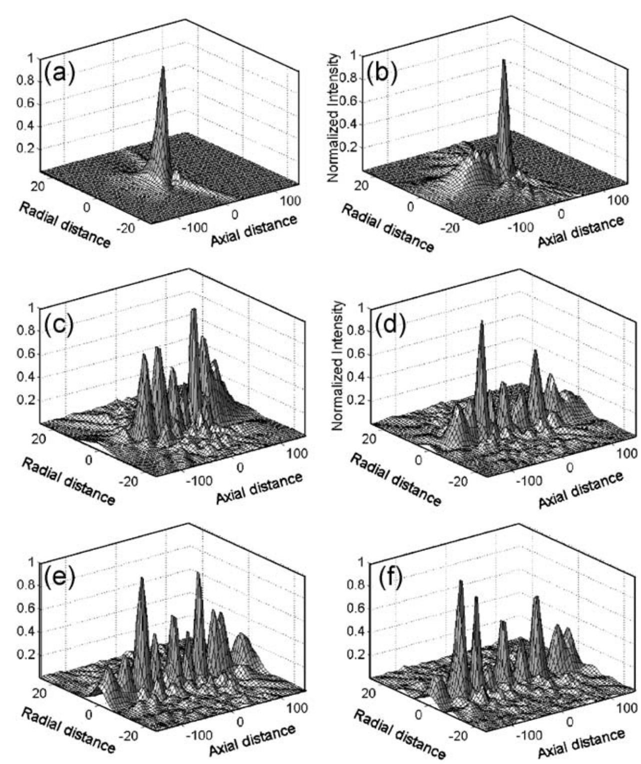

Fig. 1. Intensity distributions in focal region for $D = 1$ and C ranges from (a) $C = 1$, (b) $C = 2$, (c) $C = 4$, (d) $C = 5$, (e) $C = 6$, (f) $C = 7$.