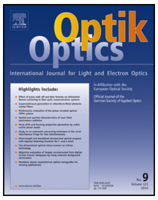
Optik 125 (2014) 6550–6553

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Focal shifting of transversely polarized beam using cosine phase plate

K. Prabakaran [a,*], K.B. Rajesh [b], T.V.S. Pillai [c]

[a] Department of Physics, Periyar University- PG Extension Centre, Dharmapuri, Tamilnadu, India
[b] Department of Physics, Chikkanna Government Arts College, Tiruppur, Tamilnadu, India
[c] Department of Physics, University College of Engineering, Nagercoil, Tamilnadu, India

ARTICLE INFO

Article history:
Received 21 November 2013
Accepted 20 June 2014

Keywords:
Focusing properties
Transversely polarized beam
Vector diffraction theory
Cosine phase plate

ABSTRACT

Focal shift of transversely polarized beams induced by cosine phase masks are investigated theoretically by vector diffraction theory. Results show that when the transversely polarized beam with radial cosine wavefront phase is focused, the focal pattern differs considerably with frequency parameter in the cosine function term. Increasing the value of frequency parameter in the cosine part of the phase mask, focal shift 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 five of multiple peaks. The tunable focal shift can be used to construct controllable optical tweezers.

1. Introduction

In recent years, research interest in nondiffracting optical beams has been steadily growing for their practical applications. 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 super resolution 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 [20,7], holographic optical tweezers arrays [21]. An interferometer pattern between two annular laser beams was also used to construct three-dimensional trapped structures within an optical tweezers setup [22].

In the optical trapping system, it is usually deemed that the forces exerted on the particles in light field include two kinds of forces; one is the gradient force, which is proportional to the intensity gradient, and the other is the scattering force, which is proportional to the optical intensity [23,24]. Therefore, the tunable focal shift predicts that the position of optical trap may be controllable. In fact, 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 [25–31]. It was 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 [27–29]. More interestingly, the focal shift may be incontinuous in certain optical focusing systems. It was 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 [30,31].

In our knowledge, the focusing properties of the transversely polarized beam with cosine phase wavefront are not studied. In fact, the polarization and phase wavefront are very important characteristics to alter propagating and focusing properties of beams [32–36]. The present paper is aimed at studying focal shift in transversely polarized beam with cosine phase wavefront by vector

---

* Corresponding author.
E-mail address: prabaphysics1986@gmail.com (K. Prabakaran).

http://dx.doi.org/10.1016/j.ijleo.2014.06.168

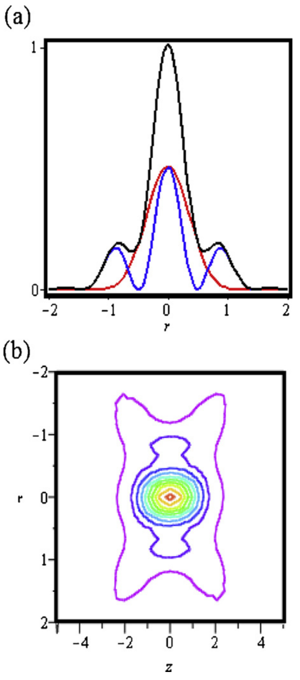


Fig. 1. (a) Two dimensional intensity profile of the radial component (Er), longitudinal component ($E\varphi$), and the total field (E_{tot}) of the focal plane, (b) shows the total electric field density distributions in the rz-plane of transversely polarized beam for the high NA lens without radial cosine phase plate. (For interpretation of the references to color in the text citation, the reader is referred to the web version of this article.)

diffraction theory, 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. The principle of the focusing transversely polarized beam is given in Section 2. Section 3 shows the simulation results and discussions. The conclusions are summarized in Section 4.

2. Principle of the optical focusing transversely polarized beam:

Based on vector diffraction theory [33], the total electric field is given as

$$E(r, z, \varphi) = Er + E\phi + Ez \tag{1}$$

The electric field near the focus under transversely polarized beam illumination can be derived in cylindrical coordinates as

$$\vec{E}(r, \phi, z) = \begin{bmatrix} Er \\ E\phi \\ Ez \end{bmatrix} = \begin{bmatrix} -Ae^{i\phi}(I_0 + I_2) \\ -IAe^{i\phi}(I_0 - I_2) \\ 0 \end{bmatrix} \tag{2}$$

where

$$I_n = \int_0^{\theta_{\max}} \cos^{1/2}(\theta) \sin \ \theta P(\theta) e^{ikz\cos(\theta)} J_n(kr \ \sin(\theta)) d\theta \tag{3}$$

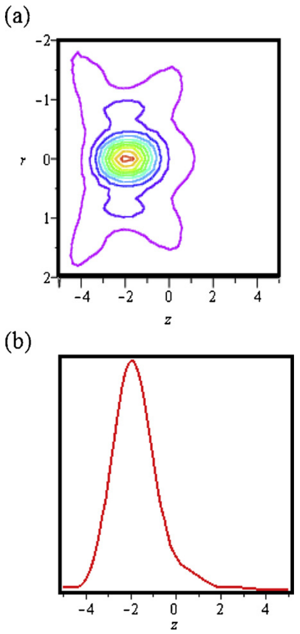


Fig. 2. (a and b) 3D and 2D intensity distributions in focal region for $C = 1$.

In Eqs. (2) and (3), $\theta_{\max}$ represents the maximum focal angle determined by the high-NA lens, k is the wave vector in free space, J_n denotes the nth-order Bessel function of the first kind, the wave front phase [37] distribution is radial cosine function distribution, and can be written as

$$P(\theta) = \pi \ \cos \left[\frac{\pi C \tan\theta}{\tan\theta \max} \right] \tag{4}$$

where C is the frequency parameter in cosine part of the wavefront phase distribution, C denotes the radial change frequency of the phase and parameter. The reason for choosing this kind of radial cosine phase wavefront is that it is very simple and easy to carry out, for example this kind of phase distribution can be implemented by phase spatial light modulator or by pure phase plate manufactured by the lithographic method conveniently.

3. Results

Without loss of generality and validity, it was proposed that NA = 0.9 and $n = 1$ in calculation process. In order to understand focusing properties of the transversely polarized beam extensively, firstly, the focusing of transversely polarized beam with high NA lens system is investigated without any wave front phase modulation. Fig. 1(a) shows the intensity profile of the radial, longitudinal and total electric field components of the optical field at focus. It is evident that the intensity of the longitudinal component (blue line) and the radial component (red line). From the Fig. 1(a), we measured the FWHM of the generated focal spot is 0.6λ and focal depth of 2.2 λ which is shown in Fig. 1(b). Secondly, the intensity distributions in focal region under condition of different phase parameter C were calculated and shown in Figs. 2–5. It should be noted that coordinate distance unit is wavelength λ. Fig. 2 illustrates the evolution of three-dimensional light intensity distribution for 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. 2(b). However when increasing C to 2, one maximum intensity peak near the optical aperture, and the maximum intensity peak also moves near from geometric plane along optical axis and is shown in Fig. 3(a) and (b). Further increasing C