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A four-quadrant phase filter for creating two focusing spots

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ABSTRACT

We present a design method of four-quadrant pure phase filter and phase modulation functions for creating two focusing spots. With the combination of a high numerical aperture objective and a four-quadrant pure phase filter, a radially polarized incident plane wave can be focused into two focusing spots with the spacing of several wavelengths along the optical axis. The filter with the phase modulation functions are verified effective by numerical simulation. The distance of the two focuses and the position of each focus can be controlled and adjusted by changing the phase modulation functions. The beam quality and longitudinally polarization purity of these two focusing spots are calculated and discussed and thus the centrally obstructed four-quadrant phase filters are proposed to improve the beam quality.

1. Introduction

The highly localized light spot formed with high numerical aperture objectives have been extensively exploited in diverse disciplines, including optical microscopy and spectroscopy [1–4], laser trapping and manipulations [5–8], optical data storage [9–10], micro/nano optical fabrication [11], plasmonic wave excitation [12] and medical therapy [13–15]. For these applications, the three dimensional intensity distribution and the polarization state distribution in the focal area of an objective have been systemically studied [16–22]. It has been shown that the intensity distribution depends on the incident laser beam mode, the polarization orientation, the phase and amplitude modulation, and the numerical aperture of the objective [23–26]. For the objective without additional aperture and illuminated by the plane wave illumination, the linear or circular polarization is preferable over radial polarization for spot size reduction. But with annular aperture and a high NA objective, the radial polarization illumination results in smaller spot sizes and reaches the limit of scalar diffraction theory. For sub-wavelength and super-resolution focusing, the polarization properties of the incident light field play an important role. Thus the vector diffraction theory has to be adopted for obtaining the exact field profile in the focal area. Vector analysis shows that the radially polarized beam can have a narrow central peak due to the appearance of the strong longitudinal field component that is sharply centered on the optical axis. It is verified that the longitudinal component generated by radially polarized illumination produces the narrow spot size for annular illumination, the total intensity profile of longitudinal component and radial component in the focal area usually have smallest spot size because the radial component cancel out each other at the focal area. The dominant longitudinally polarized light field component has been found in many applications such as tip-enhanced Raman spectroscopy [27], Z-polarized confocal microscopy [28], second-harmonic generation [29], detection of single molecule dipole moment [30] and laser particle acceleration [31–32].

Elongating focal depth is an advantage in many practical applications such as microelectronics, microscopy, and optical storage. Many methods have been proposed for increasing long focal depth such as inserting physical annular aperture at the incident pupil plane or obstructing the central part of incident light, using shade mask in which focal depth is elongated by modulating amplitude transmittance over the whole pupil aperture, and applying pure phase apodizer [33–36]. Creating a needle of longitudinally polarized light beam in the focal area using binary optics has also been proposed [37]. This binary optics works as a special polarization filter enhancing the longitudinal component. The needle of longitudinally polarized light is non-diffracting and it propagates without divergence over a distance in free space. Another form of focal intensity distribution is a conveyable quasi-periodic optical chain [38]. Analysis shows that it can stably trap and deliver multiple individual particles in three dimensions at different planes near the focus. This three-dimensional optical chain can be realized with a specially designed diffractive phase element for modulating incoming radially polarized beam. By controlling the phase modulation of the incident beam, one can manipulate the interference pattern to accelerate and transport trapped particles along the optical axis in an expected manner. With separate localizations for individual particles, the manipulation of the interference pattern may be used to decode and unravel DNA condensation without adjacent interactions.

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In this paper, we present an azimuthally sectioned phase filter for producing a two longitudinally polarized focusing spot using incident radially polarized plane wave and high numerical aperture objective. It is called four-quadrant phase filter. The phase modulation functions for each quadrant are proposed. This four-quadrant phase filter is verified effective for creating two focal spots. We also designed the centrally obstructed four-quadrant phase filter to enhance the longitudinally polarized component. A double focus intensity distribution may stably trap two micro-particles clearly separated and aligned along the optical axis.

2. The structure of a four-quadrant phase filter and its phase modulation function

For understanding the method and principle of a four-quadrant phase filter and its phase modulation function, we intuitively explain the polarization state transformation when the radially polarized light is focused by a high numerical aperture objective. When a light beam is tightly focused to a small spot, a longitudinal field component is generated at the focal plane. The appearance of the longitudinal field component is due to the bending of the light rays. The bended light rays represent tilted plane waves propagating forward to the focusing spot. Their polarization vector can be decomposed into two vector components. One is parallel to the optical axis representing the longitudinally polarized component and the other perpendicular to the optical axis representing the transversely polarized component. For the circularly symmetrical property of the objective and radially polarized incident beam, the transversely polarized component will cancel out each other on the optical axis while the longitudinally polarized component will be strengthened on the optical axis by constructive interference of plane waves propagating towards the focal plane from opposite sides of objective entrance pupil. The strengthened component is mainly concentrated on the vicinity of the optical axis forming sharper spot. We now divided the pupil plane azimuthally into four independent quadrants. As shown in the Fig. 1, quadrant 1 is opposite to quadrant 3 and quadrant 2 is opposite to quadrant 4. The transversely polarized component coming from quadrant 1 is actually canceling out with the transversely polarized component coming from quadrant 3. The identical situation occurs to the transversely polarized components coming from both quadrant 2 and quadrant 4. All the four longitudinally polarized components coming from four quadrants will still interfere with each other and the light field on the optical axis is strengthened. If we impose the same phase modulation function $P_{1,3}(r)$ on both quadrant 1 and quadrant 3, the nature of canceling out each other of the transversely polarized components and strengthening each other of longitudinally polarized components remain unchanged. Further,if we impose the same phase modulation function $P_{2,4}(r)$ which is different from the $P_{1,3}(r)$ on both quadrant 2 and quadrant 4, the resulting intensity distribution in the focal area should be different from the intensity distribution formed by the light coming through the quadrant 1 and quadrant 3. It implies that the focal plane displacements have been introduced by the phase modulation. We introduce the two phase modulations $P_{1,3}(r)$ and $P_{2,4}(r)$ as following:

$$P_{1,3}(r) = \left(kz_{1,3}\sqrt{1-(r/f)^2}\right) \quad (1)$$

$$P_{2,4}(r) = \left(kz_{2,4}\sqrt{1-(r/f)^2}\right) \quad (2)$$

where $k = 2\pi/\lambda$, λ is the wavelength. $z_{1,3}$ and $z_{2,4}$ are the distances between the original focal plane without the phase modulation and the displaced focal plane with the phase modulation. r is the polar coordinate and f is the focal distance of the objective. Fig. 2 shows the three examples of two dimensional phase modulation distribution of the four-quadrant phase filter. It is seen that, in each quadrant, the radial distribution of the phase changes in the same way but in different quadrant, it changes differently. When the absolute value of the $z_{1,3}$ or $z_{2,4}$ increases, the radial distribution of the phase changes more quickly. Fig. 3 is the schematic diagram of the focusing of the incident radially polarized beam by a high numerical aperture objective. Before the focusing, the radially polarized beam is modulated by a four-quadrant phase filter. It results in the formation of two focuses. In the focal volume, the longitudinally polarized component is dominant over the transversely polarized component for the reason stated before.

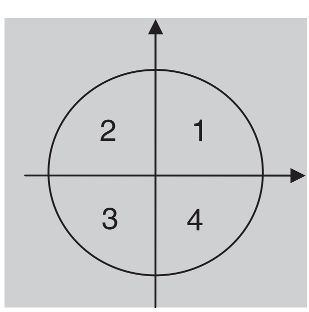

Fig. 1. The schematic diagram of dividing the pupil plane azimuthally into four independent quadrants.

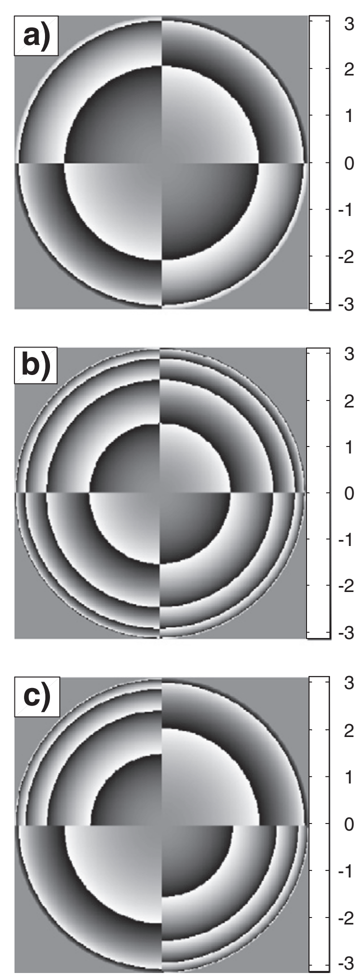

Fig. 2. Two dimensional phase modulation distribution of the four-quadrant phase filter. (a) $z_{1,3} = 2\lambda, z_{2,4} = -2\lambda$; (b) $z_{1,3} = 4\lambda, z_{2,4} = -4\lambda$; (c) $z_{1,3} = 2\lambda, z_{2,4} = -4\lambda$.