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Optics Communications 281 (2008) 1924–1928
OPTICS COMMUNICATIONS
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Numerical aperture invariant focus shaping using spirally polarized beams

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Received 25 April 2007; received in revised form 14 November 2007; accepted 23 November 2007

Abstract

The concept of spiral polarization is proposed as an extension of the generalized cylindrical vector beam. The focusing properties of this spatially variant polarization under high NA are studied. It can be shown that with one such polarization, the focus maintains a flat-top intensity shape independent of NA from NA = 0.82 up to NA = 0.95.

PACS: 42.25.Ja; 42.25.−p; 42.15.Eq

Keywords: Polarization; Laser beam shaping; Image formation theory; Optical confinement and manipulation; Cylindrical vector beams

1. Introduction

Beam shaping using spatially variant polarization has been of an increasing research interest in recent years. In dealing with two-dimensional configurations, radial and azimuthal polarizations are usually chosen as the polarization basis states due to symmetry considerations. Using this basis, the generalized cylindrical vector beam [1] has been proposed as a linear combination of radial and azimuthal components as shown in Fig. 1. Mathematically, the generalized cylindrical vector beam can be expressed as [1] $\vec{E}(r,\phi) = P[\cos\varphi_0\,\vec{e_r} + \sin\varphi_0\,\vec{e_\phi}]$, where $\vec{e_r}$ and $\vec{e_\phi}$ are the radial and azimuthal basis polarizations, respectively. The relative strength of the radial and azimuthal components is determined by the rotation angle φ_0 from the radial direction.

This generalized cylindrical vector beam is shown to be quite useful in beam shaping [1] under high numerical aperture (NA), which is due to the special focusing properties of radial and azimuthal polarization. (Here NA is defined as NA $= \sin\theta$, where focusing in the air is assumed.) For a given (high) NA, the focal field intensity distribution of the radially polarized light has a peak at the center, contributed by the strong z-component [1,2]; the focal pattern of the azimuthally polarized light has a null at the center, with only the transverse component and no z-component in place. So by changing the angle φ_0 of the generalized cylindrical vector beam, we can balance the z-component and the transverse components to yield a flat-top focus. For example, in Ref. [1], Zhan and Leger have shown that for NA = 0.8, with the rotation angle φ_0 of 24°, the focal intensity shape is flat-top, as is shown in Fig. 1b. Such uniform irradiance is very important in a variety of applications, such as laser micro machining [3], laser-assisted thermal annealing [4], optical recording [5] etc. Other beam shapes can also be realized by appropriate polarization modulation. For example, the annular-shaped spot resulting from the transverse-only polarization component has certain advantages in materials processing and micro-welding [6,7]. One inconvenient aspect of this polarization beam shaping scheme involves adjusting the angle φ_0 for different NA's. Fig. 2 shows the NA dependence of the rotation angle φ_0 for the generalized cylindrical vector beam to

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doi:10.1016/j.optcom.2007.11.093

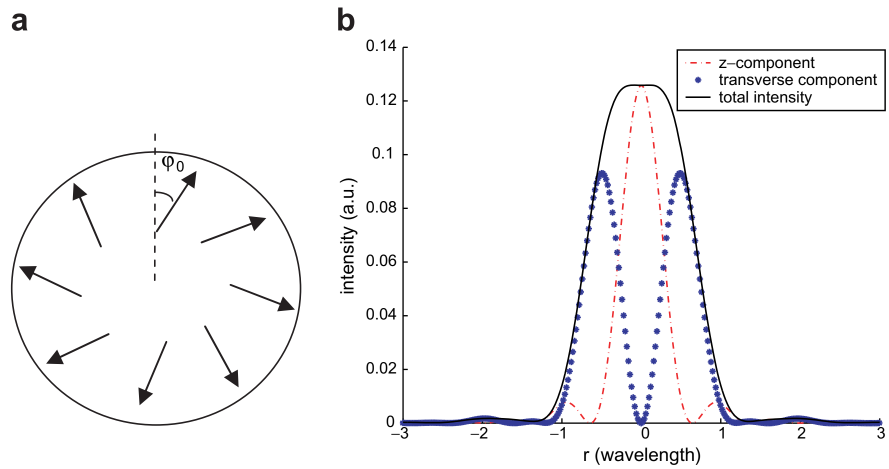

Fig. 1. (a) Schematic of generalized cylindrical vector beam. φ_0 is the rotation angle from the radial direction. (b) The flat-top intensity distribution in the focal plane produced by (a), NA = 0.8 and $\varphi_0 = 24^\circ$.

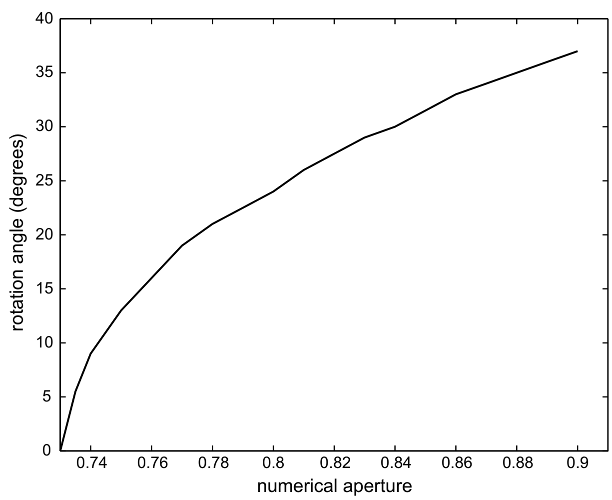

Fig. 2. Rotation angle φ_0 as a function of numerical aperture to achieve a flat-top beam at focus.

produce a flat-top focal pattern. It can be clearly seen in Fig. 2 that as the NA increases, the characteristic angle φ_0 that achieves flat-top beam shaping also becomes larger. In practice, the changing of the angle φ_0 is usually performed by mechanically rotating a wave-plate to some prescribed orientation.

In this paper, we propose another polarization beam shaping method based on the use of "spiral polarization", which is an extension of the generalized cylindrical vector beam concept. By numerical simulation, we show that one such polarization family is capable of delivering the flat-top focal pattern invariant to NA, from NA = 0.82 up to NA = 0.95.

2. System configuration and numerical simulation

Spiral polarization is another kind of spatially variant polarization bearing radial symmetry. By extending the generalized cylindrical vector beam concept, we let the rotation angle φ_0 be a function of radius ρ, which typically has a larger value as ρ increases. Thus the instantaneous electric vector at various points follows the shape of a spiral line, resulting in the coined name "spiral polarization". Fig. 3 shows the schematic plots of the spiral polarization, which starts off almost radial at the center and curves towards azimuthal polarization at the edge. At each point, the polarization can be decomposed into radial and azimuthal basis components and hence preserves radial symmetry. Depending on the specific form of the function $\varphi_0(\rho)$, where ρ denotes the radius, the "spiral lines" curve in different patterns.

The focusing properties of the spirally polarized beam can be analyzed using the Richards and Wolf [8] vectorial diffraction theory to take into account the spatial inhomogeneity vector property. This method is extensively used when considering high NA imaging and focusing in applications such as lithography and optical recording. Furthermore, in dealing with radial and azimuthal polarization or the generalized cylindrical vector beam, this method has been routinely employed and the integral formula can be shown to take a relatively simple form [1,2].

The geometry of the beam shaping problem is shown in Fig. 4. The incident beam bearing the spiral polarization is focused by an aplanatic high numerical aperture lens. The

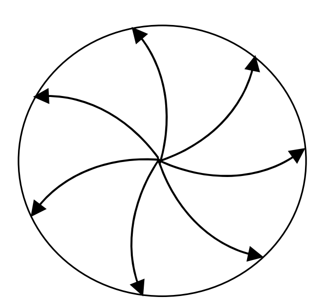

Fig. 3. Schematic of spiral polarization.