O E L E T T E R S

Generation and focusing of radially polarized electric fields

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Abstract. The use of radially polarized light is known to produce, when focused by a high-numerical-aperture objective lens, a spot of light whose polarization is predominantly axial. We have generated accurately such radially polarized fields, which we have coupled into a high-numerical-aperture microscope objective so as to produce an axially polarized focal spot.
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1 Introduction

The ability to accurately generate an arbitrary scalar complex optical wavefront is important in many fields from optical shop testing to adaptive optic applications. In this latter case it is desirable to be able to reconfigure these wavefront shapes as quickly as possible.[1,2] There are, however, an increasingly large number of instances in which it is desirable to create arbitrary vectorial beams in which the polarization is spatially varying. Examples range from studies of singularities in optical fields[3] to the tuning of the strength of the longitudinal component of the electric field in the focal region of a microscope objective for single molecular experiments.[4] These applications require, for example, the use of radially and azimuthally polarized light. In this paper we will generate such beams accurately using a ferroelectric liquid crystal spatial light modulator (FLCSLM) in an appropriate 4-f optical system[5] and show experimentally, for the case of radially polarized light, that we are able to produce an axially polarized electric field in the focus of a high-aperture microscope objective.

2 Theory

Figure 1 shows the focusing action of an objective lens when radially polarized light is incident. The incident beam is refracted by the lens toward the focus and, as can be seen, the refraction leads to the presence of an axially polarized component in the focal field.

The relative strength of the radial and axial polarization components of the focal field is determined by the numerical aperture. It is to be expected that the strength of the axial component will be enhanced at higher values of numerical aperture. However even at a numerical aperture of unity, Fig. 2(a), it is evident that a significant lateral component is still present. In order to further suppress this component, annular apodization may be used. Figures 2(b) and 2(c) illustrate the process. Indeed, in the limit of extreme annular illumination, Figs. 2(b) and 2(d), where the axial polarization dominates, the focal distribution is given by $J_0^2(v)$, where v is a normalized coordinate related to actual focal plane coordinate r via $v=(2\pi/\lambda)rn\sin(\alpha)$, where λ denotes the wavelength and $n\sin(\alpha)$ represents the numerical aperture. We note that this focal distribution is both radially symmetric and considerably narrower than the corresponding asymmetric focal distribution obtained with linearly polarized light. The theoretical curves in Fig. 2 were obtained using the approach described by Richards and Wolf.[6]

3 Experimental

As we have seen, the use of a radially focused incident wave causes a very tightly focused spot with a predominantly axially polarized electric field to be produced in the focal region of a high-numerical-aperture objective lens. It is therefore immediately attractive to consider using such beams in a variety of applications where either the small spot size and/or the axial polarization is important. In this section we will demonstrate that it is possible to accurately generate radially polarized beams and to couple such beams into a high-numerical-aperture microscope objective so as to produce an axially polarized field in the focal plane. We use the reconfigurable FLCSLM approach[5] to produce a radially polarized beam, which is then arranged to be incident on the aperture of a high-numerical-aperture microscope objective. In order to confirm that we have indeed produced an axially polarized field in the focus, we elect to place a subresolution point scatter in the focal region and to examine the form of the field scattered back through the objective lens. It is clear from Fig. 1 that the polarization of the electric field on-axis at the focal point is purely axial. We assume that the scatter is sufficiently small that it radiates as an electric dipole[7] whose dipole moment is proportional to the electric field of the incident light, Fig. 3. The far-field radiation pattern, from the (dipole) scatterer, may be written as $E=-r_{\wedge}(r_{\wedge}p)$ where p is the dipole moment. We note, of course, that $E\cdot r=0$, i.e., no component along the propagation direction r It is then a simple matter to refract this field by the objective lens to find the field E_2 in the back focal plane. For our special case in which the dipole radiates as p_z only it is a simple matter to write the field in the back focal plane, dashed line in Fig. 3, as

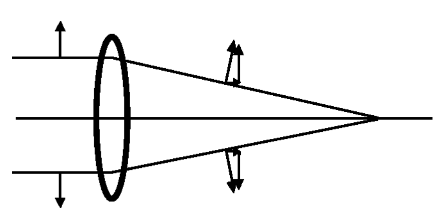

Fig. 1 Schematic diagram showing the electric field components of a radially polarized beam when it is focused by an objective lens.

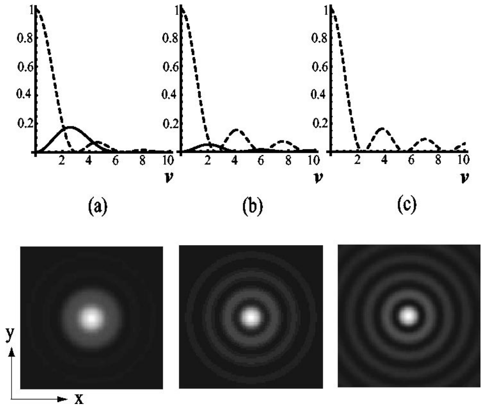

Fig. 2 Relative strengths of the lateral (solid line) and axial (dashed line) components of the electric field in the focal plane of an objective lens, NA=1.0: (a) no apodization; (b) and (c) 80% and 99% annular apodization, respectively; (d), (e), and (f) corresponding form of the focal spot $|E|^2$.

$$E_2 \sim \frac{\sin\theta}{\sqrt{\cos\theta}} \begin{pmatrix} \sin\phi \\ \cos\phi \end{pmatrix} \qquad (1)$$

where the $\sqrt{\cos\theta}$ factor takes account of the change in the direction of the energy stream.[6] For objective lenses obeying the sine condition we may introduce a radial coordinate in the pupil plane $\rho = \sin\theta/\sin\alpha$. Figure 4 shows the intensity in the back focal plane when a 100-nm gold bead was placed on axis in the focal plane and the objective lens was illuminated with a radially polarized field. Good agreement between theory and experiment is obtained, which confirms

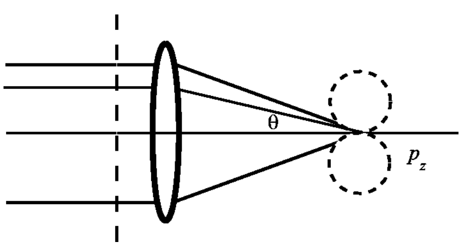

Fig. 3 The use of radially polarized light results in a purely axially polarized electric field at the geometrical focus. A point scatterer located at focus radiates as a dipole with a far-field pattern (dashed lines).

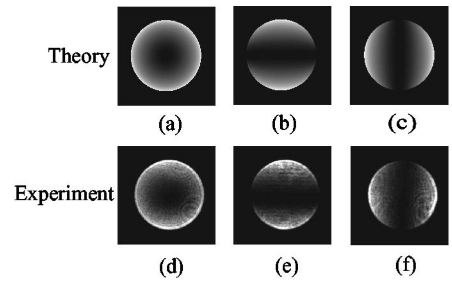

Fig. 4 (a) and (d) Theoretical and experimental back focal plane intensities. (b), (e) and (c), (f) The vectorial nature of the field is revealed with the aid of "horizontal" and "vertical" linear polars, respectively. The objective used was a 63X, 1.4-NA oil immersion objective and a 0.532-μm laser was used as the light source.

that we have indeed been able to generate an axially polarized field and, as expected, zero intensity is found in the center of the pupil.

4 Conclusions

We have discussed the use of radially polarized incident waves together with high-aperture microscope objectives. It is found that a very tightly focused spot of light can be obtained but with predominently axial polarization at high numerical aperture and we have confirmed this behavior experimentally by observing the dipole field produced by a subresolution scatterer.

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