Experimental verification on tightly focused radially polarized vortex beams*

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The theoretical and experimental results of tightly focused radially polarized vortex beams are demonstrated. An auto-focus technology is introduced into the measurement system in order to enhance the measurement precision, and the radially polarized vortex beams are generated by a liquid-crystal polarization converter and a vortex phase plate. The focused fields of radially polarized vortex beams with different topological charges at numerical apertures (NAs) of 0.65 and 0.85 are measured respectively, and the results indicate that the total intensity distribution at focus is dependent not only on the NA of the focusing objective lens and polarization pattern of the beam but also on the topological charge l of the beam. Some unique focusing properties of radially polarized vortex beams with fractional topological charges are presented based on numerical calculations. The experimental verification paves the way for some practical applications of radially polarized vortex beams, such as in optical trapping, near-field microscopy, and material processing.

Keywords: vortex beams, radial polarization, tight focusing

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1. Introduction

Optical vortex beams have received much attention due to their unique properties and many potential applications in optical tweezers, optical transformations, rotational frequency shifting, and optical vortices, which have resulted in a new branch of singular optics in modern optics.[1] Optical vortex beams possess a helical phase structure of $\exp(\mathrm{i}l\phi)$, where l is the topological charge of the beams and ϕ is the azimuthal angle in the cylindrical coordinate system. Especially, vortex beams with space-variant polarization (also called vector vortex beams) have aroused the interests of some researchers due to their different optical properties from those of vortex beams with space-invariant polarization (also called scalar vortex beams). It has been demonstrated[2–5] that the vector vortex beams can be generated using subwavelength metallic and dielectric gratings at 10.6 μm. Zhan and Leger[6] measured the spiral phase distributions of cylindrically polarized vortex beams generated by a dichroic radial analyzer, and Zhan[7] studied theoretically the high-numerical aperture (NA) focusing properties of circularly polarized vortex beams. Rao *et al.*[8] and Zhang *et al.*[9] numerically calculated the high NA focused fields of cylindrically polarized and spirally polarized vortex beams respectively. We further presented the experimental results of tightly focused vector vortex beams with high polarization orders based on a con-focal microscopy system.[10] But to the best of our knowledge, the experimental results of tightly focused radially polarized vortex beams have not been reported until now.

To fill the gap, we present the experimental results of tightly focused radially polarized vortex beams based on a high NA focusing system, and an auto-focus technology is introduced into the measurement system in order to enhance the measurement precision. The radially polarized vortex beams are generated by a liquid-crystal polarization converter and a vortex phase plate, and several kinds of such beams with different topological charges are obtained. The focused fields at NAs of 0.65 and 0.85 are measured respectively, which verify the reported theoretical results, and the experimental verification establishes the foundation for some practical applications of radially polarized vortex beams.

2. Theoretical and experimental results

First, we assume that the radially polarized vortex beam can be expressed in a cylindrical coordinate system as

$$\boldsymbol{E}_{\mathrm{in}} = E_0 P(r) \exp(\mathrm{i}l\phi)\, \boldsymbol{e}_r, \tag{1}$$

where E_0 is a constant, $P(r)$ the axially symmetric amplitude distribution of the beam, l the topological charge of the beam, ϕ the azimuthal angle, and $\boldsymbol{e}_r$ the unit vector in the radial direction.

Then, the radially polarized vortex beam is incident upon a high NA objective lens, and according to the results reported

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in Ref. [8], the focal field of a radially polarized vortex beam can be written as

$$\begin{aligned} & E_{\text{out}}(r_{\text{S}}, \phi_{\text{S}}, z_{\text{S}}) \\ = & \begin{bmatrix} E_r^{(S)} \\ E_z^{(S)} \end{bmatrix} \\ = & \ \mathrm{i}^l E_0 \exp(\mathrm{i}l\phi_{\text{S}}) \int_0^{\alpha} \sqrt{\cos\theta} \sin\theta P(\theta) \exp(\mathrm{i}kz\cos\theta) \\ & \times \begin{bmatrix} \cos\theta \left[\mathrm{J}_{l+1}(kr\sin\theta) - \mathrm{J}_{l-1}(kr\sin\theta)\right] \\ 2\mathrm{i}\sin\theta J_l(kr\sin\theta) \end{bmatrix} \mathrm{d}\theta. \end{aligned} \tag{2}$$

Here, $S(r_{\text{s}}, \varphi_{\text{s}}, z_{\text{s}})$ is an observation point near focus; E_r and E_z are the amplitudes of the radial and longitudinal components respectively; $P(\theta)$ is the pupil apodization function which denotes the relative amplitude and phase of the incident beam; k is the wavelength number; θ denotes the focusing angle (the angle between the optical axis and the propagation vector). So the relationship between the maximum of θ and NA of the objective lens is given by $\alpha = \sin^{-1}(NA/n)$, where n is the refractive index of the surrounding medium. In Eq. (2), J_{l-1}, J_l, and J_{l+1} are the Bessel functions of the first kind with orders $l-1$, l, and $l+1$, respectively. In the case, the azimuthal component disappears and only the radial and longitudinal components are present, so the total intensity is the sum of the radial intensity and longitudinal intensity. Moreover, it is seen that the focused field intensity distribution can be easily understood by analyzing the Bessel function J_l of Eq. (2). Only $l = 0$ and $l = 1$ each give rise to a non-zero optical intensity on the optical axis, however, for other topological charges $l > 1$, the focused field intensity on the optical axis is zero due to destructive interference.

Next, a measurement system as shown in Fig. 1 is built in order to measure the tightly focused fields of radially polarized vortex beams, where a He–Ne laser is used to emit a light beam at 633 nm. The light beam first passes through a filter, and it is collimated by a collimator, then incident onto a linear polarizer that passes through two reflectors. The transmitted linearly polarized beam is incident onto a liquid-crystal polarization converter (ARCoptix Swizerland, radial polarization converter, http://www.arcoptix.com), which can convert the incident linearly polarized beam into a radially polarized beam. The generated radially polarized beam then passes through a vortex phase plate (RPC Photonics, Inc., VPP-m633, http://www.RPCphotonics.com) to achieve a radially polarized vortex beam. Note that the optical vortex beams with topological charges from $l = 1$ to $l = 8$ can be obtained by adjusting the incident radially polarized beam to pass through different sections of the vortex phase plate. Then the radially polarized vortex beams with different topological charges can be focused by a high NA objective lens, and the focused fields are measured by a CCD camera. In order to enhance the measurement precision, an auto-focus system with movement step length of 0.1 μm is introduced and the ideal focal plane can be positioned using the technology.

Figure 2 shows the calculated and measured intensity distributions at focus for $NA = 0.65$ and topological charges $l = 1$, 2, 3, and 4, respectively, and by comparison, figure 3 further shows the experimental and theoretical results for $NA = 0.85$. In the calculations,

$$P(\theta) = \exp\left[-\left(\frac{\sin\theta}{\sin\alpha}\right)^2\right] \mathrm{J}_1\left(2\frac{\sin\theta}{\sin\alpha}\right)$$

is chosen and all length measurements are in units of wavelength. It can be seen from the experimental results that the focused intensity distribution of radially polarized vortex beams with $l = 1$ is a confined focal spot and the total intensity is nonzero on the optical axis. But the focused intensity distribution for $l > 1$ is a confined focal hole, and the total intensity is zero on the optical axis. Furthermore, the size of focal hole increases with the increase of topological charge, and decreases with the NA of the focusing objective increasing. The measured results are in agreement with the theoretical results, which verifies the theoretical analysis and also indicates that the focused field intensity distribution can be modulated flexibly by the NA of the objective lens and topological charges of beams. The measured errors are mainly attributed to the deviations of phase and polarization distribution of generated radially polarized vortex beams from those of ideal beams.

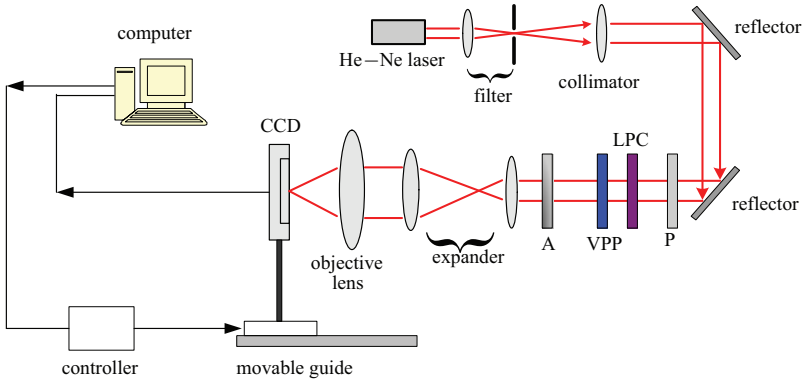


Fig. 1. (color online) Illustration of experimental set-up, where P denotes the polarizer, LPC the liquid-crystal polarization converter, VPP the vortex phase plate, and A the attenuator.

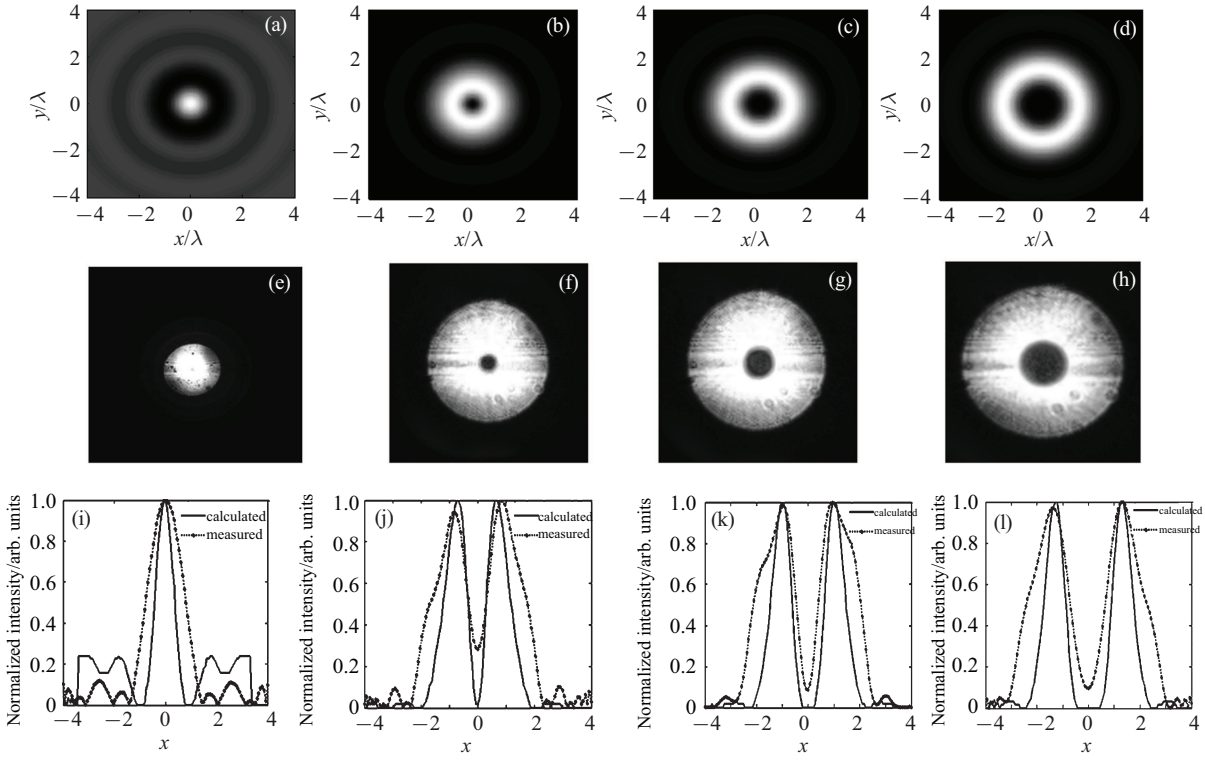


Fig. 2. The calculated (the first row) and measured (the second row) intensity distributions of radially polarized vortex beams at focus for $NA = 0.65$; and the intensity distributions along x axis for calculated and measured results (the third row), respectively, panels (a), (e), and (i) for $l = 1$; (b), (f), and (j) for $l = 2$; (c), (g), and (k) for $l = 3$; (d), (h), and (l) for $l = 4$.

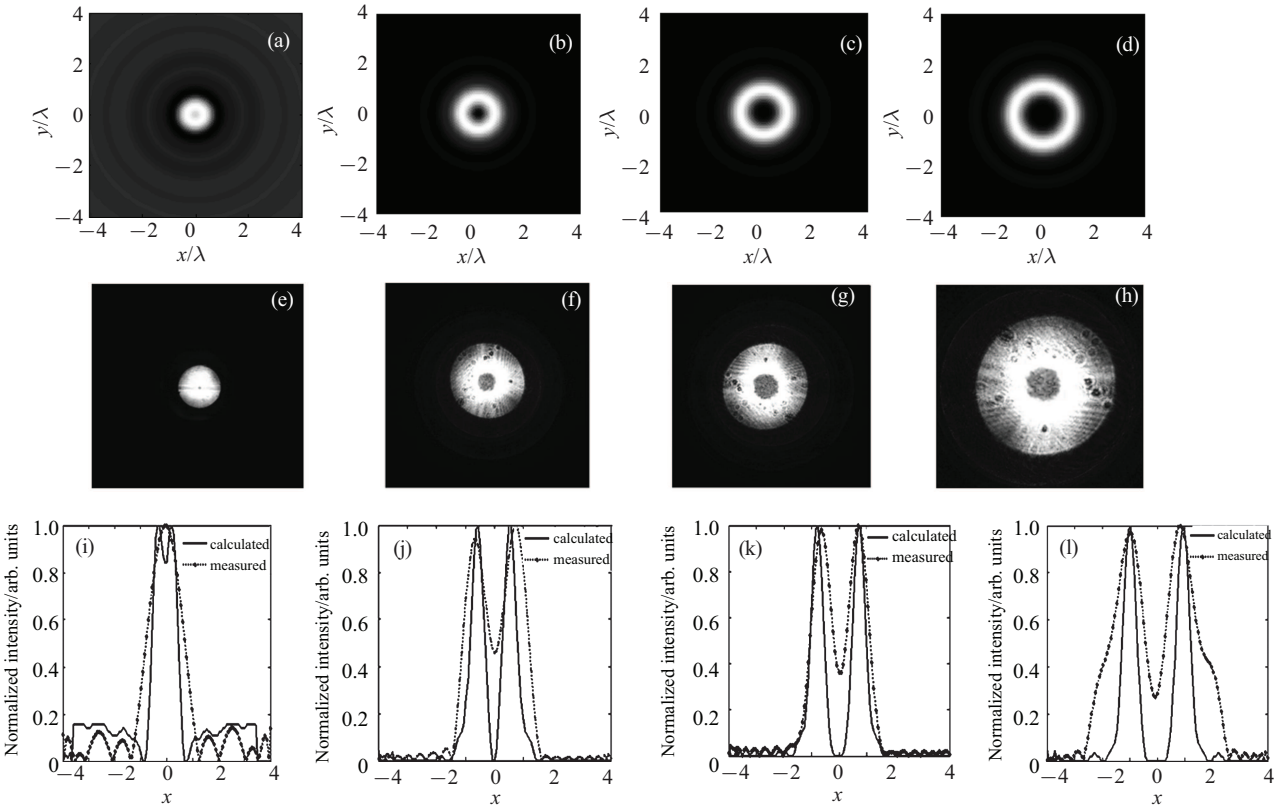


Fig. 3. The calculated (the first row) and measured (the second row) intensity distributions of radially polarized vortex beams at focus for $NA = 0.85$; and the intensity distributions along x axis for calculated and measured results (the third row), respectively, panels (a), (e), and (i) for $l = 1$; (b), (f), and (j) for $l = 2$; (c), (g), and (k) for $l = 3$; (d), (h), and (l) for $l = 4$.

Finally, it is worth noting that the vortex beams with fractional topological charges have been widely reported in the past several years.[11–13] But to the best of our knowledge, the tightly focusing of radially polarized vortex beams with fractional topological charges has not been studied yet. Using Eq. (2), we calculate the focused field intensity distributions of radially polarized vortex beams with fractional topological charges $l = 0.5$, 1.5, 2.5, 3.5, and 4.5 at $NA = 0.65$, and the results are shown in Fig. 4. Obviously, the intensity pattern of a radially polarized vortex beam with fractional vortex structure is distinguished from that of an integer-order vortex beam. The focused field is not annularly symmetric but about the y axis, and the intensity is not zero on the optical axis. Interestingly, the focused field possesses a radial opening (low-intensity gap) in the annular intensity ring encompassing the dark spot. These unique focusing properties may lead to some novel optical phenomena and find wide applications in optical trapping and particle manipulation.[14]

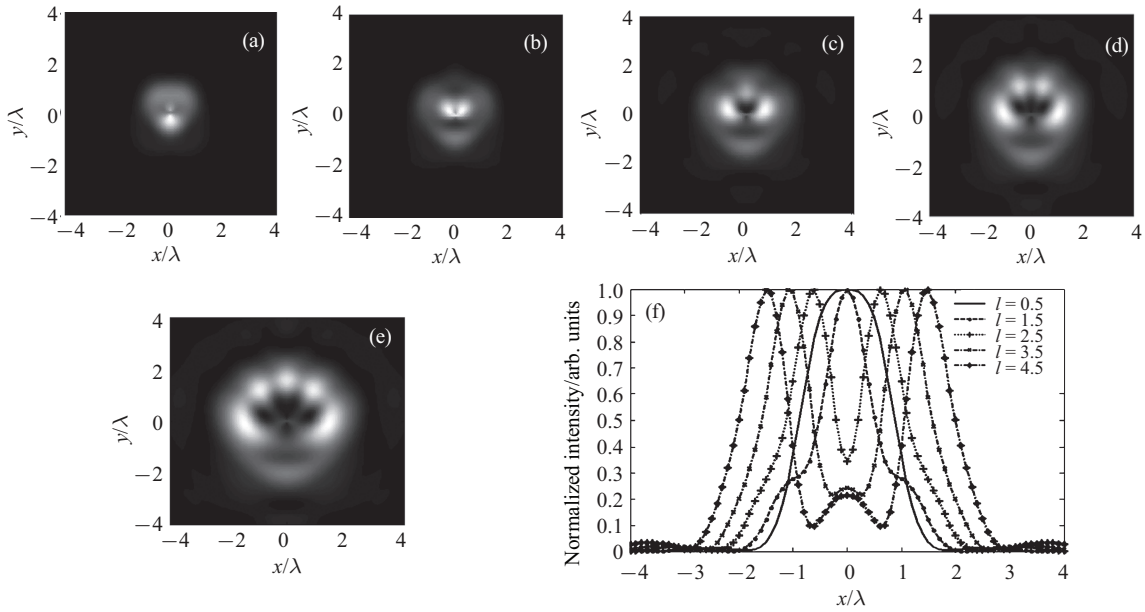


Fig. 4. The calculated intensity distributions of radially polarized vortex beams at focus for $NA = 0.65$, where panel (a) for $l = 0.5$, (b) for $l = 1.5$, (c) for $l = 2.5$, (d) for $l = 3.5$, (e) for $l = 4.5$, and the intensity distributions along x axis for calculated results (f).

3. Conclusions

We demonstrated the experimental results of tightly focused intensity distributions of radially polarized vortex beams with topological charges $l = 1$, 2, 3, and 4 based on a built high-NA focusing system, where an auto-focusing system is used to enhance the measurement precision. The experimental results are in good agreement with the theoretical results, which indicates the focused field intensity distribution can be modulated flexibly by changing the topological charge and NA of the focusing lens. In addition, the focused fields of radially polarized vortex beams with fractional topological charges are calculated numerically, and the results demonstrate some unique focusing properties different from those of integer-order vortex beams. These theoretical and experimental results shown in the paper may stimulate some potential applications of radially polarized vortex beams in optical trapping, near-field microscopy, and material processing.

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