Experimental investigation on partially coherent higher-order non-diffractive beams*

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(Received 17 February 2011; revised manuscript received 16 April 2011)

We experimentally study the generation of a partially coherent non-diffractive beam by focusing a partially coherent vortex beam with an axicon. The investigation results show that when the partially coherent vortex beam is focused by the axicon, the beam is transferred into a partially coherent higher-order non-diffractive beam. In the non-diffractive zone, the transverse intensity distribution of the partially coherent higher-order non-diffractive beam is invariant during propagation. In addition, the range of the non-diffractive zone is related to the coherence of the partially coherent vortex beam. The poorer the coherence of the partially coherent vortex beam, the shorter the range of the non-diffractive zone.

Keywords: physical optics, higher-order non-diffractive Bessel beam, axicon, partially coherence

PACS: 42.25.Fx, 42.25.Kb **DOI:** 10.1088/1674-1056/20/9/094203

1. Introduction

A vortex beam has a twist phase front and an intensity of zero in the centre of the beam. In its expression, there is a phase factor $\exp(\mathrm{i}m\theta)$. Each photon of the vortex beam carries an orbital angular momentum of $m\hbar$, where m is the topological charge and $\hbar$ is the reduced Planck constant.[1,2] The vortex beam has an orbital angular momentum, thus it can be potentially applied in the fields of quantum information processing, particle trapping, etc.[3−11] Higher-order Laguerre–Gaussian beams and higher-order Bessel beams have twist phase fronts and are typical vortex beams. Compared with other vortex beams, the higher-order Bessel beam is as non-diffractive as the zero-order Bessel beam.[12,13] Thus, since Durnin *et al.*[12] introduced the concept that the zero-order Bessel beam is non-diffractive, research on the higher-order Bessel beam has become a hot spot.[14−16] Moreover, owing to the fact that partially coherent light is universal and has advantages such as a more uniform intensity distribution and a low sensitivity to speckle compared with completely coherent light, if the higher-order Bessel beam is partially coherent, it is quite interesting to generate it and to study its propagation. In the present paper, by using the phase modulation for partially coherent light with a spiral phase plate, the partially coherent vortex beam can be generated and then by focusing it with an axicon, we can achieve a so-called partially coherent higher-order Bessel beam.

2. Theoretical background

In the experimental device shown in Fig. 1, through the rotating ground glass, the beam becomes a partially coherent one and its cross-spectral density is of the Gauss–Schell mode.[17,18] Then phase modulation is applied to it by using the spiral phase plate and it becomes a partially coherent vortex beam. Thus, the cross-spectral density of the partially coherent vortex beam on the axicon can be described by

$$\begin{aligned} &W(\boldsymbol{r}_1, \boldsymbol{r}_2, z=0) \\ &= \Big(\frac{r_1}{w}\Big)^m \Big(\frac{r_2}{w}\Big)^m \exp\Big(-\frac{r_1^2+r_2^2}{w^2}\Big) \\ &\quad \times \exp[-\mathrm{i}m(\theta_1-\theta_2)] \exp\Big[\frac{-(r_1-r_2)^2}{\delta^2}\Big], \end{aligned} \quad (1)$$

where w is the waist radius of the Gaussian beam, m is the topological charge of the partially coherent vortex beam and δ denotes the coherent length of the partially coherent beam. An axicon is employed to focus the partially coherent vortex beam to form a partially coherent higher-order non-diffractive beam. The

*Project supported by the National Natural Science Foundation of China (Grant No. 60977068) and the Foundations of the State Key Laboratory for Transient Optical and Photonic Technology of Chinese Academy of Sciences (Grant No. SKL ST200912).

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cross-spectral density of the partially coherent higher-order non-diffractive beam can be described as

$$\begin{aligned} & W(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2, z) \\ = & \left(\frac{k}{2\pi z}\right)^2 \iint W(\boldsymbol{r}_1, \boldsymbol{r}_2, z=0) \\ & \times \exp\left\{-\frac{\mathrm{i}k}{2z}\left[(\boldsymbol{\rho}_1 - \boldsymbol{r}_1)^2 - (\boldsymbol{\rho}_2 - \boldsymbol{r}_2)^2\right]\right\} \\ & \times \exp[-\mathrm{i}k(n-1)\gamma r_1]\exp[-\mathrm{i}k(n-1)\gamma r_2]\mathrm{d}\boldsymbol{r}_1\mathrm{d}\boldsymbol{r}_2, \end{aligned} \tag{2}$$

where $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ refer to the horizontal vector coordinates of the beam at the focusing field, z is the longitudinal length from the axicon, n is the index of refraction of the axicon, k is the wave number and γ denotes the bottom angle. The axicon does not affect the orbital angular momentum. Therefore, the order of the partially coherent non-diffractive beam is equal to the topological charge of the incident beam. Equation (2) can be further changed into

$$\begin{aligned} W(\rho_1, \rho_2, \theta_1, \theta_2, z) = & \left(\frac{k}{2\pi z}\right)^2 \exp\left[-\mathrm{i}\frac{k}{2z}(\rho_1^2 - \rho_2^2)\right] \iiiint \exp\left[\frac{\mathrm{i}k}{2z}(r_1^2 - r_2^2)\right] \\ & \times \exp[-\mathrm{i}m(\varphi_1 - \varphi_2)] \times \left(\frac{r_1}{w}\right)^m \left(\frac{r_2}{w}\right)^m \exp\left[-\left(\frac{1}{w^2} + \frac{1}{\delta^2}\right)(r_1^2 + r_2^2)\right] \\ & \times \exp\left[\frac{\mathrm{i}kr_1\rho_1}{z}\cos(\theta_1 - \varphi_1)\right] \exp\left[-\frac{\mathrm{i}kr_2\rho_2}{z}\cos(\theta_2 - \varphi_2)\right] \exp\left[\frac{r_1 r_2}{\delta^2}\cos(\varphi_1 - \varphi_2)\right] \\ & \times \exp[-\mathrm{i}k(n-1)\gamma r_1]\exp[-\mathrm{i}k(n-1)\gamma r_2] r_1 r_2 \mathrm{d}r_1 \mathrm{d}r_2 \mathrm{d}\varphi_1 \mathrm{d}\varphi_2. \end{aligned} \tag{3}$$

The following formula can be obtained from the integral of Eq. (3),

$$\begin{aligned} W(\rho_1, \rho_2, \theta_1, \theta_2, z) = & \left(\frac{k}{2\pi z}\right)^2 \exp\left[-\mathrm{i}\frac{k}{2z}(\rho_1^2 - \rho_2^2)\right] \sum_{l=-\infty}^{\infty} \iint \exp\left[\frac{\mathrm{i}k}{2z}(r_1^2 - r_2^2)\right] \left(\frac{r_1}{w}\right)^m \left(\frac{r_2}{w}\right)^m \\ & \times \exp\left[-\left(\frac{1}{w^2} + \frac{1}{\delta^2}\right)(r_1^2 + r_2^2)\right] \exp[-\mathrm{i}k(n-1)\gamma r_1] \exp[-\mathrm{i}k(n-1)\gamma r_2] \exp[-\mathrm{i}l(\theta_1 - \theta_2)] \\ & \times \mathrm{J}_l\left(\frac{kr_1\rho_1}{z}\right) \mathrm{J}_l\left(\frac{kr_2\rho_2}{z}\right) \mathrm{I}_{l+m}\left(\frac{2r_1 r_2}{\delta^2}\right) r_1 r_2 \mathrm{d}r_1 \mathrm{d}r_2, \end{aligned} \tag{4}$$

where J is the Bessel function of the first kind and I is the modified Bessel function. If $\rho_1 = \rho_2 = \rho$ and $\theta_1 = \theta_2 = \theta$, the cross-spectral density is simplified into the intensity distribution of the beam, which is given by

$$\begin{aligned} W(\rho, \theta, z) = & \left(\frac{k}{2\pi z}\right)^2 \sum_{l=-\infty}^{\infty} \iint \exp\left[\frac{\mathrm{i}k}{2z}(r_1^2 - r_2^2)\right] \left(\frac{r_1}{w}\right)^m \left(\frac{r_2}{w}\right)^m \exp\left[-\left(\frac{1}{w^2} + \frac{1}{\delta^2}\right)(r_1^2 + r_2^2)\right] \\ & \times \exp[-\mathrm{i}k(n-1)\gamma r_1] \exp[-\mathrm{i}k(n-1)\gamma r_2] \mathrm{J}_l\left(\frac{kr_1\rho}{z}\right) \mathrm{J}_l\left(\frac{kr_2\rho}{z}\right) \mathrm{I}_{l+m}\left(\frac{2r_1 r_2}{\delta^2}\right) r_1 r_2 \mathrm{d}r_1 \mathrm{d}r_2. \end{aligned} \tag{5}$$

Equation (5) is the luminous intensity of the partially coherent vortex beam at the focusing field after it has passed through the axicon. From Eq. (5), we can see that the intensity distribution of the partially coherent vortex beam is independent of azimuth angle θ, thus the intensity distribution of the beam is symmetrical at the cross section.

3. Experimental setup and results

Figure 1 shows the schematic diagram for the generation of the partially coherent higher-order non-diffractive beam. A rotating ground glass is placed near the common focus of the two lenses with the same focus. Because of the destruction of the beam wave front by the rotating ground glass, the completely coherent beam becomes a partially coherent one after it has passed through the lenses. Then, the partial coherent beam goes through an spiral phase plate (SPP) and finally becomes a partially coherent vortex beam. The SPP can modulate the wave-front phase of the beam. When the beam passes through the SPP, its wave-front phase is changed into a spiral one. The central light intensity of the partial coherent vortex beam is not zero. By using the axicon to focus the partial coherent vortex beam, the beam is changed into a partially coherent higher-order non-diffractive beam. The coherence of the partially coherent beam

is controlled by the position of the rotating ground glass. The coherence is best when the rotating ground glass is at the common focus of the two lenses. The further the beam is away from the common focus, the larger the size of the wave front through the ground glass is and the worse the coherence is. In addition, by using different spiral phase plates, partially coherent vortex beams with different topological charges can be obtained to study the effect of the topological charge on the non-diffraction of the partially coherent higher-order non-diffractive beam.

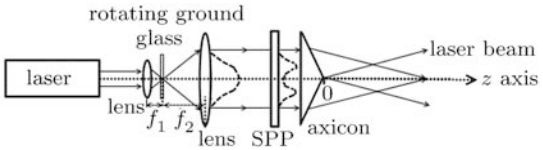


Fig. 1. Schematic diagram of the partial coherent vortex beam focused by an axicon.

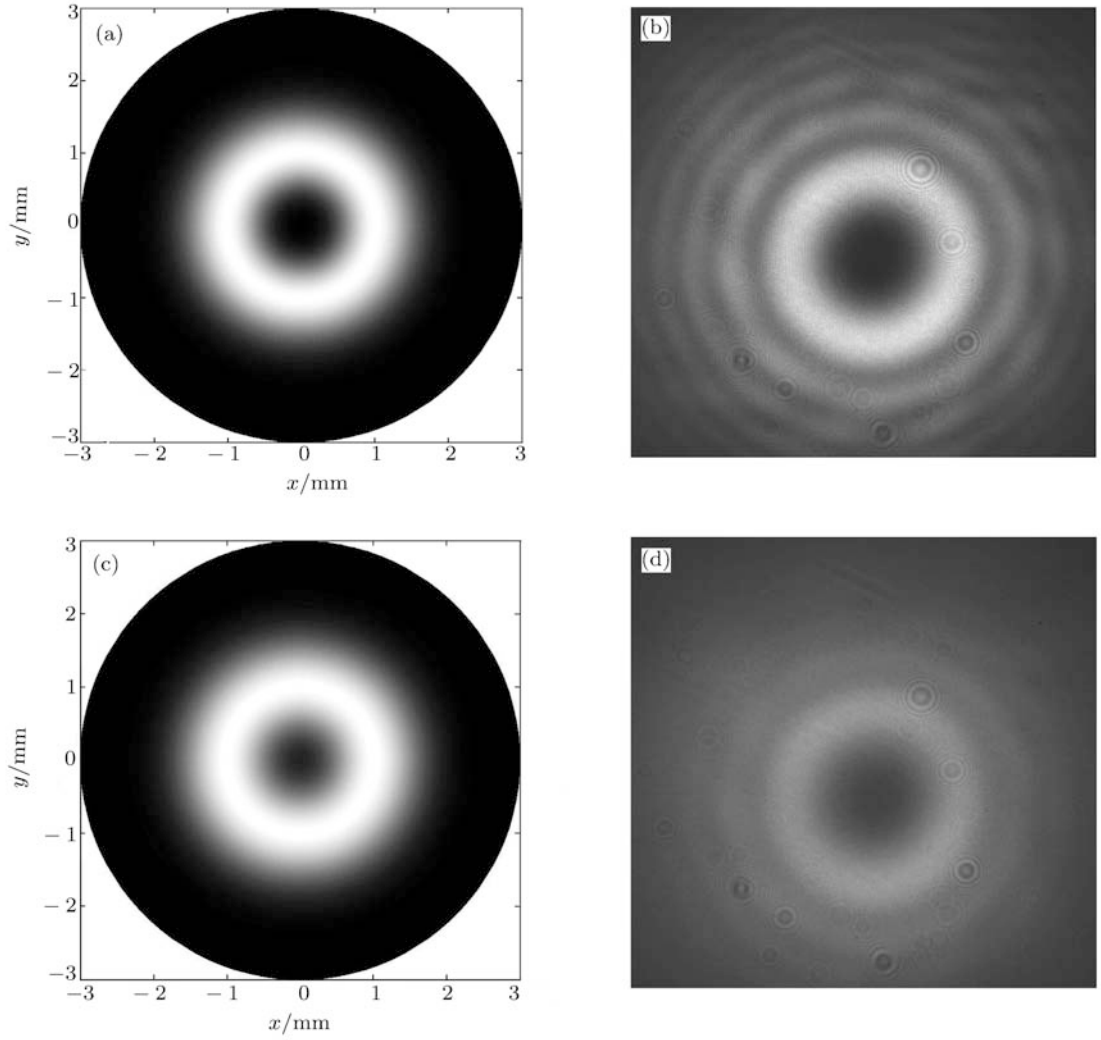


Fig. 2. Intensity distributions of the partially coherent vortex beam ($m = 2$). Panels (a) and (c) show numerical simulations, and panels (b) and (d) indicate experimental results, with coherent length δ equals 1.13 mm (a), 1.13 mm (b), 0.554 mm (c) and 0.554 mm (d), and the other parameters are $w = 1$ mm, $\lambda = 632.8$ nm.

In Figs. 2(a) and 2(c), we plot the theoretical intensity distributions of the partially coherent vortex beams of topological charge $m = 2$ and with coherent lengthes of 1.13 mm and 0.554 mm, respectively. The corresponding experimental results are given in Figs. 2(b) and 2(c). As shown in Fig. 2, when the coherent length decreases, the dark centre becomes small and changes somewhat in light. The partially coherent higher-order non-diffractive beams can be obtained by focusing the partially coherent higher-order non-diffractive beams with an axicon. In Fig. 3, we plot the intensity distributions of the obtained partially coherent higher-order non-diffractive beam at four different positions. The relevant parameters are as follows:

$\delta = 0.67$ mm, the bottom angle of the axicon γ is 0.5° and the index of refraction n is 1.5. It can be seen from Fig. 3 that the partially coherent higher-order non-diffractive beam is non-diffractive behind the axicon. At positions $z = 5$ cm, $z = 15$ cm and $z = 25$ cm, the horizontal intensity distributions do not change. However, after the focused beam transfers over 25 cm, for example at position $z = 50$ cm, the intensity distribution changes obviously. This means that position $z = 50$ cm is outside the non-diffractive range. Thus, by focusing the first-order partially coherent vortex beam, we can obtain the first-order partially coherent non-diffractive beam. When the coherent length δ is 0.67 mm, the non-diffractive range is nearly 25 cm.

Figure 4 also shows the focus of the first-order partially coherent vortex beam. The coherent length of the incoming partially coherent vortex beam is 0.57 mm and the other parameters are the same as those shown in Fig. 3. We can see from Fig. 4 that in the focusing field, when the distance is no more than 20 cm, the horizontal intensity distribution after the beam has been focused by the axicon does not change obviously and is still non-diffractive to a certain degree. When the distance is beyond 20 cm, the horizontal intensity distribution of the focused beam changes obviously and is not non-diffractive any more. Therefore, when the coherent length of the incoming partially coherent beam is 0.57 mm, the non-diffractive distance is nearly 20 cm. From Figs. 3 and 4, we can draw the conclusion that the smaller the coherence length of the partially coherent higher-order vortex beam is, the smaller its non-diffractive range is.

Figure 5 shows the horizontal intensity distributions of the first-order completely coherent non-diffractive beam when there is no rotating ground glass. From the horizontal intensity distribution, we can see that at $z = 50$ cm, the status of no diffraction is good in the intensity distribution of the focused beam and, compared with Fig. 3, the non-diffractive distance is obviously much larger.

Figure 6 shows the horizontal intensity distributions of the partially coherent vortex beam with a topological charge of 2 and a coherent length of 0.67 mm after it has been focused by the axicon. The other parameters are the same as those shown in Fig. 3. From the four images shown in Fig. 6, we can see that when the distance is no more than 25 cm, the focused beam is a little diffractive. Thus by focusing the partially coherent vortex beam with the topological charge of 2 with the axicon, we can obtain a second-order partially coherent non-diffractive beam.

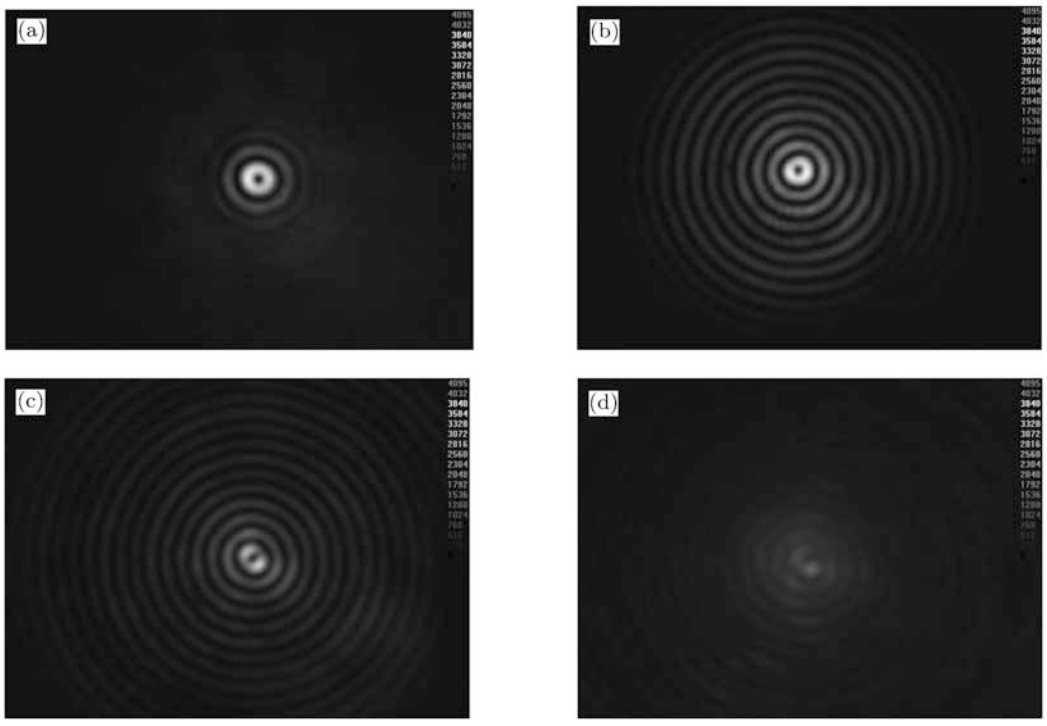


Fig. 3. Intensity distributions of the first-order partially coherent non-diffractive beam at $z = 5$ cm (a), 15 cm (b), 25 cm (c) and 50 cm (d), with the value of the topological charge being 1, coherent length $\delta = 0.67$ mm, $\gamma = 0.5$ and $n = 1.5$.

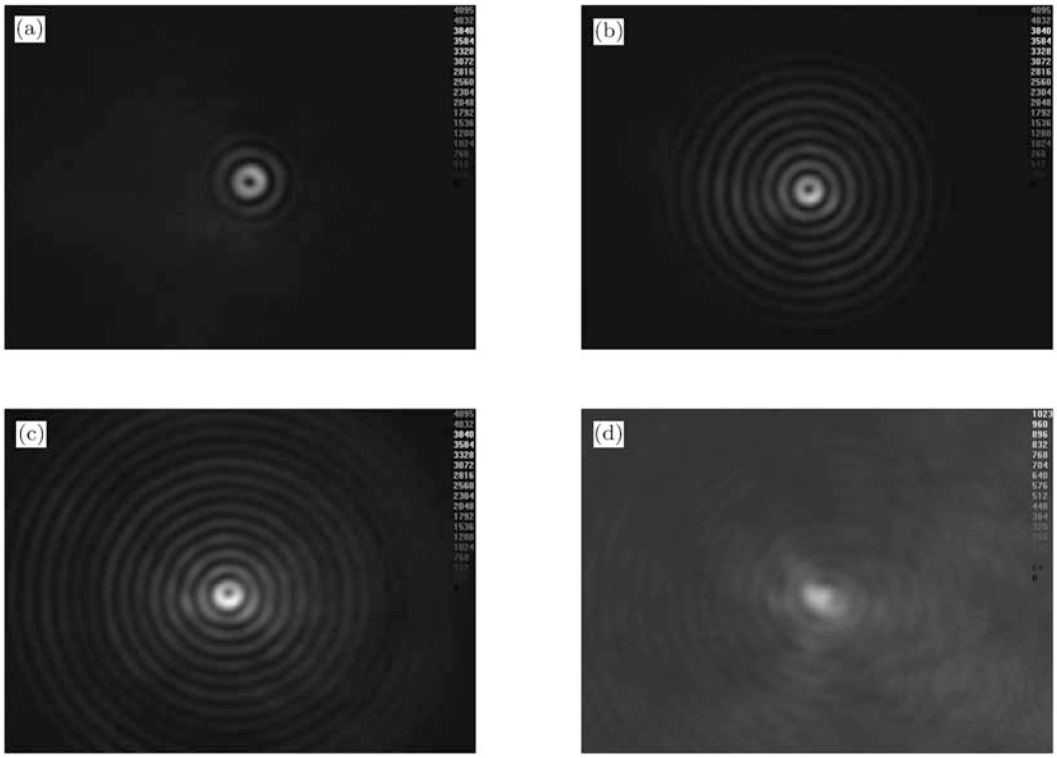


Fig. 4. Intensity distributions of the first-order partially coherent non-diffractive beam at $z = 5$ cm (a),15 cm (b), 20 cm (c) and 40 cm (d), with the value of topological charge being 1, coherent length $\delta = 0.57$ mm, $\gamma = 0.5$ and $n = 1.5$.

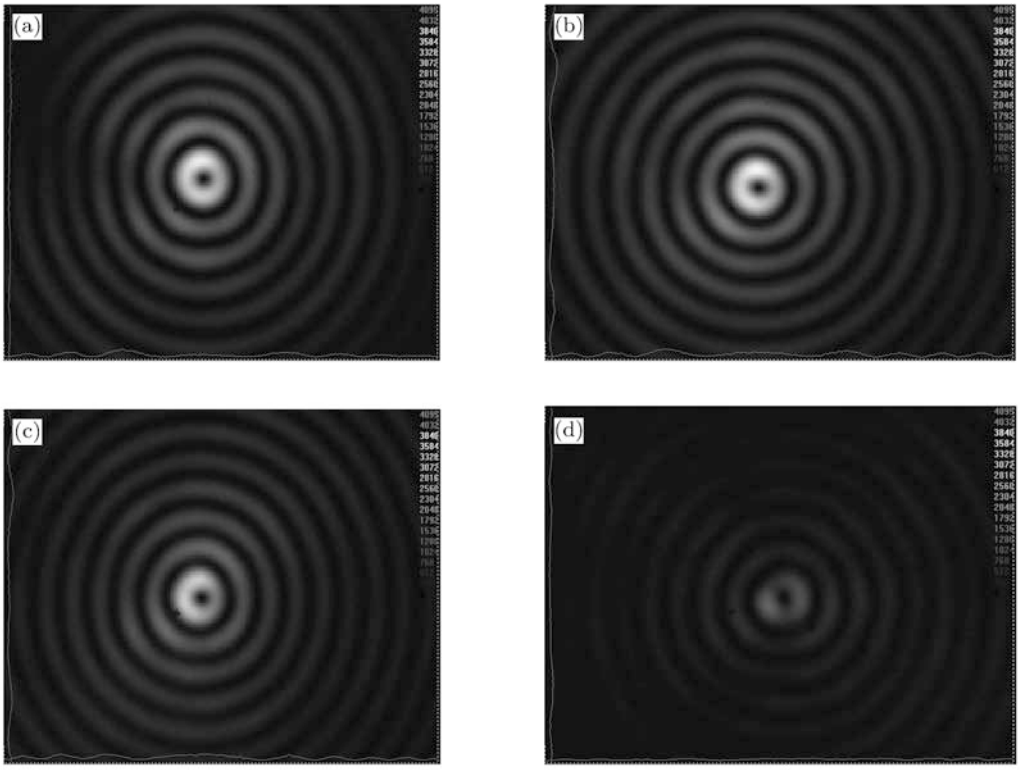


Fig. 5. Intensity distributions of the first-order completely coherent non-diffractive beam without a rotating ground glass at $z = 15$ cm (a), 20 cm (b), 25 cm (c) and 50 cm (d), with the value of topological charge being 1, $\gamma = 0.5$ and $n = 1.5$.

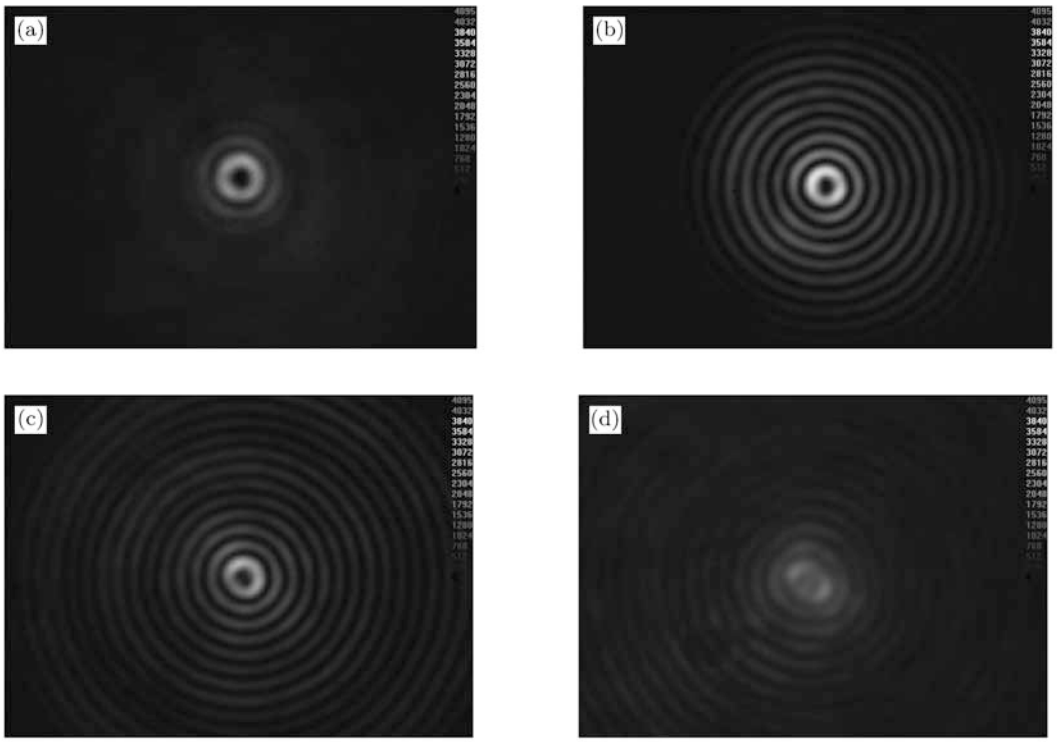


Fig. 6. Intensity distributions of the second-order partially coherent non-diffractive beam at $z = 5$ cm (a), 15 cm (b), 25 cm (c) and 50 cm (d), with the value of topological charge being 2, coherent length $\delta = 0.67$ mm, $\gamma = 0.5$ and $n = 1.5$.

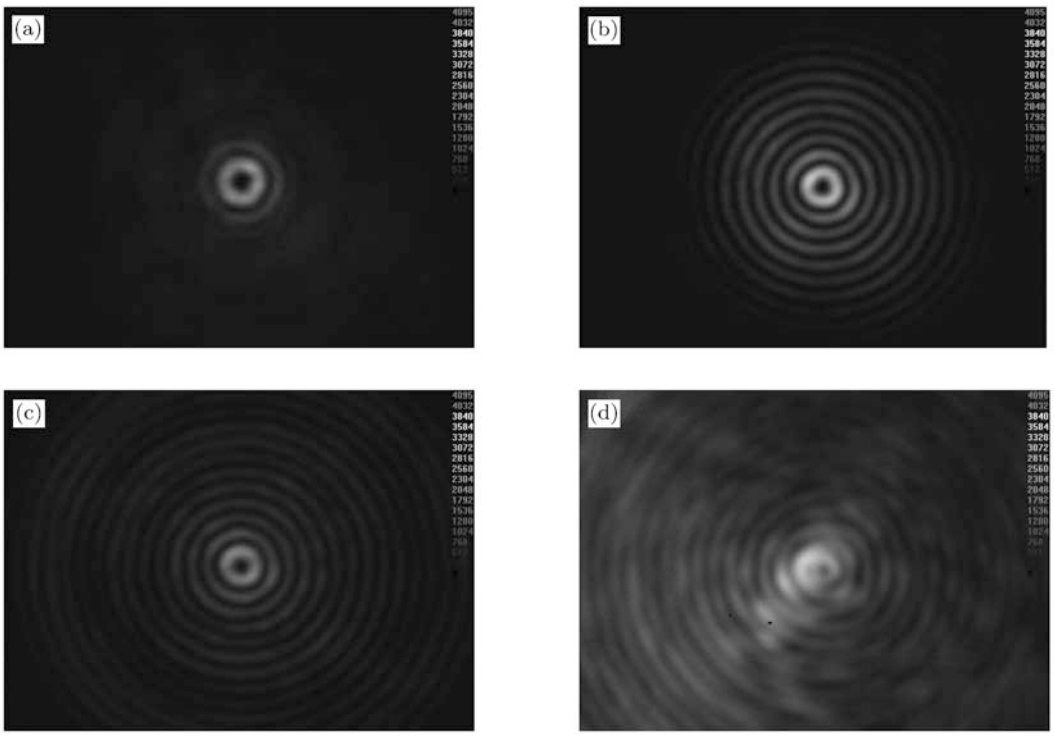


Fig. 7. Intensity distributions of the second-order partially coherent non-diffractive beam at $z = 5$ cm (a), 15 cm (b), 20 cm (c) and 40 cm (d), with the value of topological charge being 2, coherent length $\delta = 0.57$ mm, $\gamma = 0.5$ and $n = 1.5$.

Figure 7 shows the intensity distribution of the partially coherent vortex beam with a coherent length of 0.57 mm after it has been focused by the axicon. Compared with the scenario shown in Fig. 6, though the coherent length of the incoming partially coherent vortex beam is smaller, the partially coherent non-diffractive beam can be obtained after it has been focused by the axicon. In Fig. 7, the non-diffractive distance of the beam is only 20 cm. By comparison with Figs. 3–5, we can see that the non-diffractive distance of the partially coherent non-diffractive beam after it has been focused by the axicon is related to the coherent length of the incoming partially coherent beam. In other words, the better the coherence of the incoming partially coherent beam, the larger the non-diffractive distance of the partially coherent non-diffractive beam.

4. Conclusion

In this paper, we experimentally study the focusing of a partially coherent vortex beam through an axicon. The results indicate that a partially coherent vortex beam can be changed into a partially coherent higher-order non-diffractive beam. The order of the resulting partially coherent non-diffractive beam is the same as the topological charge of the incoming vortex beam. By comparing the focuses of the vortex beams of different coherences, we can find that the better the coherence of the partially coherent vortex beam is, the larger the non-diffractive distance of the partially coherent non-diffractive beam produced after being focused by the axicon is. The obtained partially coherent higher-order non-diffractive beam is not only a vortex beam, but also possesses non-diffractive properties. Moreover, due to the fact that the partially coherent beam is less influenced by speckle, this new kind of beam can be applied to optical trapping, atmospheric propagation, etc.

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