Annals of Physics 360 (2015) 549–555

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Quantitative comparison of self-healing ability between Bessel–Gaussian beam and Airy beam

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ARTICLE INFO

Article history:
Received 13 August 2014
Accepted 26 May 2015
Available online 1 June 2015

Keywords:
Self-healing ability
Bessel-beam
Airy beam
Propagation

ABSTRACT

The self-healing ability during propagation process is one of the most important properties of non-diffracting beams. This ability has crucial advantages to light sheet-based microscopy to reduce scattering artefacts, increase the quality of the image and enhance the resolution of microscopy. Based on similarity between two infinite-dimensional complex vectors in Hilbert space, the ability to a Bessel–Gaussian beam and an Airy beam have been studied and compared. Comparing the evolution of the similarity of Bessel–Gaussian beam with Airy beam under the same conditions, we find that Bessel–Gaussian beam has stronger self-healing ability and is more stable than that of Airy beam. To confirm this result, the intensity profiles of Bessel–Gaussian beam and Airy beam with different similarities are numerically calculated and compared.

1. Introduction

Self-healing ability during propagation process is one of the most interesting properties of non-diffracting beams [1–11]. This property makes these beams an interesting candidate for wide applications. For example, this unusual property of Airy beams leads to a new feature in optical micromanipulation [2]; a holographically shaped and scanned Bessel beam not only reduces scattering artefacts, but also simultaneously increases the quality of the image and penetration in dense media [8,9]. Self-healing ability of Bessel beam offers advantages to overcome the losses of quantum

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http://dx.doi.org/10.1016/j.aop.2015.05.024
0003-4916/

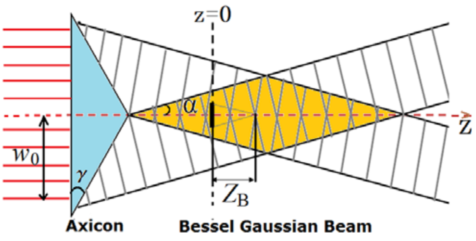

Fig. 1. Generation geometry of Bessel–Gaussian beam by using an axicon.

entanglement between photon pairs in free-space quantum communication or between quantum processing systems [12].

Over the past decade, self-healing ability of beams has stimulated substantial research interest [1,4,5,13–16]. From these research results it can be seen that there are many differences between the mechanisms of self-healing. For example, self-healing of a Bessel beam has been explained by considering the dynamics of the conical waves [17]; the explanations of self-healing ability of an Airy beam have been given by using the method of uniform geometrical optics and catastrophe optics [18,19]. The different mechanisms of these beams lead to different self-healing abilities.

Lately, the contrasts and resolutions of light-sheet microscopy created by Gaussian beam, Airy beam and Bessel beam have been put under comparisons. It was found that both Airy beam and Bessel beam yield high contrast and resolution which go up to a tenfold larger field of view [20]. However, the best beam among them to enhance the contrast and resolution of light-sheet microscopy has not been given yet. To the best of our knowledge, the comparison of self-healing ability between any beams has not been made until now.

Similarity can be used to quantitatively estimate the difference between beams [21,22]. For example, the difference between closest field and target function has been studied by using similarity [21]. Because self-healing ability of an Airy beam and a Bessel beam has been widely studied due to the flexible applications [4,8,9,16], in this paper the comparison of the self-healing ability between Airy beam and Bessel beam has been established.

2. Theory analysis

Because of the infinite-energy, Airy beam and Bessel beam are impossible in practice [23]. One of the possible ways to realize such beams is through Bessel–Gaussian (BG) beam and an exponentially truncated Airy beam. BG beam can be obtained from Gaussian beam passing through an axicon (as shown in Fig. 1) [17].

For simplicity, we assume that an obstacle with radius R is located at the $z = 0$ plane. The expression for a zeroth-order BG beam just before the obstacle is given as [24–27]

$$E_{B0}\left(r_0, z=0\right) = J_0\left(kr_0 \sin\alpha\right) \exp\left(-\frac{r_0^2}{w_0^2}\right), \tag{1}$$

where J_0 represents the zeroth-order Bessel function of the first kind, $\vec{r}_0 = (x_0, y_0)$ with (x_0, y_0) being the transverse coordinates, $k = 2\pi/\lambda$ and λ is the wavelength, w_0 is the waist width of Gaussian part, $\alpha = (n-1)\gamma$ is the opening angle of the cone, n is the refractive index and γ is the opening angle of the axicon (see Fig. 1) [17]. Based on angular spectrum theory, the optical field of BG beam at z-plane can be obtained and is given by [17]

$$E_B\left(r, z\right) = \frac{w_0^2 k}{w_0^2 k + 2iz} J_0\left(\frac{w_0^2 k^2 \sin\alpha}{w_0^2 k + 2iz} r\right) \exp\left[-\frac{k\left(r^2 + 2z^2\right)}{w_0^2 k + 2iz} + \frac{w_0^2 k^2 zi \cos\alpha}{w_0^2 k + 2iz}\right], \tag{2}$$

where z denotes the propagation distance and $\vec{r} = (x, y)$ is the transverse coordinates at z-plane. BG beam which is partially obstructed by an opaque obstacle can be expressed from Babinet principle,