

A precise method for analyzing Bessel-like beams generated by broadband waves

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ABSTRACT

The current study proposes spectrum analysis, which is a novel analytical method proposed for the first time, for analyzing Bessel-like beams generated by broadband wave. The main idea is to decompose the consecutive spectrum into an incoherent superposition of a series of different wavelengths. Integrating spheres play a significant role in spectrum analysis and a series of wavelengths matched with relative intensity can be read according to the spectrum measured by an integral ball. Moreover, the Sellmeier dispersion equation, which indicates that the refractive index can be matched with wavelength, is also employed. Combining with the Fresnel diffraction integral formula, the distribution of fields behind an axicon is obtained. Two broadband sources, including a light-emitting diode (LED) with a narrow band and a halogen lamp with a broad band, are used to generate a Bessel-like beam. The experimental results fit well with the theoretical analysis.

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1. Introduction

The Bessel beam, a special solution of wave equation in free space, has attracted the interest of numerous scholars since 1987, when Durnin first proposed it [1]. The Bessel beam has the following notable characteristics: the size of the center spot is invariant with transmission distance when it spreads in free space, the light intensity is very high at the center spot, and it can be reconstructed when it encounters obstacles [2]. These characteristics indicate that the Bessel beam can be used in a wide range of areas, such as particle trapping [3], particle optical guidance [4], statistical physics [5], atom optics [6], and the recently proposed optical tension [7]; ideally, the Bessel beam requires infinite energy, which is impossible in practice. But generating a Bessel-like beam is feasible. In the current experiment, the coherence superposition of countless plane waves, which was realized via parallel light vertically incident on an axicon, was used to generate a Bessel-like beam. Compared with other methods, such as computer holography [8,9], axicon oscillation cavity [10] and circular seam [11], axicon offers significant advantages including high light throughput efficiency, high damage threshold and simplicity.

So far, investigation on generating Bessel-like beams using a laser has developed, and our laboratory has successfully obtained

a Bessel-like beam. In recent years, some scholars generated Bessel-like beams [12–14] using incoherent waves and obtained certain achievements. Fischer [12] and cooperators have explored the Bessel beams generated by several kinds of incoherent sources. This was a huge step in Bessel beam research. Such beams could be used in particle trapping and optical guidance as well [15]. For example, a broadband Bessel-like beam improved image resolution in optical coherence tomography (OCT) [16]. Generating a Bessel-like beam by incoherent light has realistic significance. With the development of the research, a Bessel-like beam generated using incoherent light requires examination through a set of precise analytical methods. Although it is difficult to find precise analysis from literatures, Fischer [17] has investigated how a laser with three wavelengths generated a Bessel-like beam.

In the current study, a Bessel-like beam generated using a broadband wave is analyzed based on the theory of generating such beams with a field of single wavelength incident on an axicon, and adding the properties of incoherent light. A broadband wave generates a Bessel-like beam because it transforms into partially coherent light after passing through a pinhole. The wave with the same wavelength is regarded as coherent light and the wave with different wavelengths is regarded as incoherent. Based on the theoretical analysis, the coherent light generates a Bessel-like beam while the incoherent light only has an incoherent superpose. In the current study, the spectrum of the incoherent light source was analyzed precisely. The broadband wave was decomposed into a series of different wavelengths with relative intensity matched with each wavelength according to the spectrogram measured by an integral sphere. Finally, the intensity

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distribution of the cross-section of the beam was obtained by superposing the field of different wavelengths behind the axicon. In addition, the results of analyses on Bessel beam generated by monochrome LED and halogen lamp are compared with the experiment. It shows that the intensity profiles of the cross-section of the beam obtained from the theoretical simulation fitted the experimental results well. Therefore, the rationality of spectrum analysis was proven in this study. Spectrum analysis is precise and easy to understand. The smaller the wavelength interval you select, the more precise the results; so one can select the interval of wavelengths according to accuracy requirement.

2. Analysis on Bessel-like beam with diffraction theory

The vertical field distribution of a parallel light with single wavelength incident on the axicon can be derived from the Fresnel diffraction integral formula in cylindrical coordinate using the

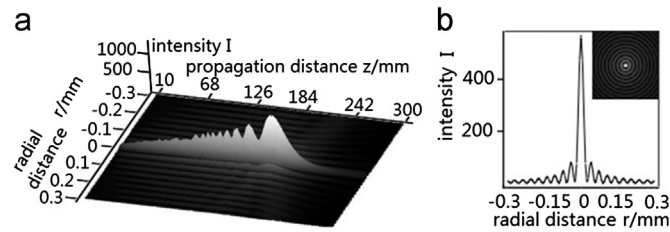


Fig. 1. (a) Intensity distribution along propagation distance and (b) intensity distribution of the cross-section of the beam.

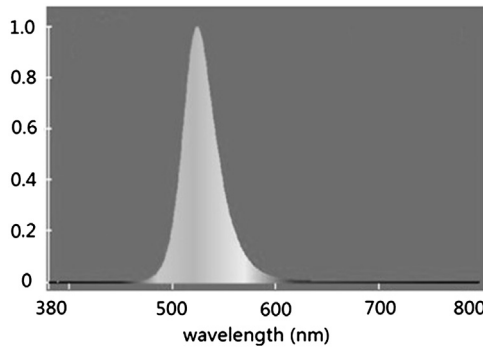


Fig. 2. LED spectrum.

Table 1
Relative intensities matched with different wavelengths.

Wavelength ($\lambda/\mu\text{m}$)	0.485	0.490	0.495	0.500	0.505	0.510	0.515
Relative intensity	0.038	0.072	0.132	0.237	0.4	0.621	0.847
Wavelength ($\lambda/\mu\text{m}$)	0.520	0.525	0.530	0.535	0.540	0.545	0.550
Relative intensity	0.992	1	0.89	0.731	0.583	0.455	0.332
Wavelength ($\lambda/\mu\text{m}$)	0.555	0.560	0.565	0.570	0.575	0.580	0.585
Relative intensity	0.25	0.185	0.137	0.1	0.074	0.054	0.039

transmission function of the axicon $t(r) = \exp[-ik(n-1)\gamma r]$ [18] given by

$$E(r_2, z) = \left(-\frac{ik}{z}\right) \exp(ikz) \exp\left(\frac{ikr_2^2}{2z}\right) \times \int_0^R E(r_1, z) J_0\left(\frac{kr_1 r_2}{z}\right) \exp\left[\frac{ikr_1^2}{2z} - ik(n-1)\gamma r_1\right] r_1 dr_1, \quad (1)$$

where $k=2\pi/\lambda$ is the wave vector, r_1 is the radial coordinate of incidence plane on axicon, r_2 is the radial coordinate of the receiving plane, $E(r_1, z)$ is the incident light field, which can be regarded as 1, n is the refractive index of the axicon, γ is the base angle of the axicon, and R is the radius of the beam incident axicon. The distribution of light intensity behind the axicon is given by

$$I(r_2, z) = |E(r_2, z)|^2 \quad (2)$$

Assuming $R=1.8$ mm, $\gamma=1^\circ$, and $\lambda=0.53$ μm , the on-axis intensity and the intensity distribution of the cross-section of the beam along the propagation distance according to Eqs. (1) and (2) were simulated, as shown in Fig. 1. As can be seen in Fig. 1, the Bessel-like beam was generated using a plane wave of single wavelength and axicon.

3. Analysis on spectrum

The lightwave impinging the axicon has a certain wavelength bandwidth instead of a single wavelength when an LED source was employed here. Fig. 1 shows the spectrum of an LED source measured by integrating spheres (PMS-80, product by Everfine, Hangzhou, China). The dominant wavelength is $\lambda=0.531$ μm , the half-peak width of the spectrum is $\Delta\lambda=0.036$ μm , and the main range of the wavelength is $\lambda=0.485$ – 0.585 μm . The coherence of the field should be discussed first, because Bessel-like beam is realized via the coherent superposition of countless plane waves with the same deflection angle, while the spectrum of the LED field contains not just a single wavelength, as shown in Fig. 2. Only the fields with the same frequency or wavelength can be coherent, and the degree of coherence between two different wavelengths is zero. In general, the superposition of same wavelengths represents the superposition of field strength, whereas superposition among different wavelengths represents the superposition of intensity.

The superposition of the field of single wavelength can generate a Bessel-like beam after passing through the axicon, and superposing the intensity of Bessel-like beams generated by the field of all wavelengths can give the final distribution of intensity behind the axicon. In this study, the wave is decomposed into a series of different wavelengths. A series of relative intensities matched with wavelengths was obtained when the interval was $\Delta\lambda=5$ nm, as shown in Table 1.

The Sellmeier dispersion equation gives a refractive index matched with different wavelengths [19] as follows:

$$n(\lambda) = \sqrt{1 + \frac{B_1 \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \lambda^2}{\lambda^2 - C_3}} \quad (3)$$

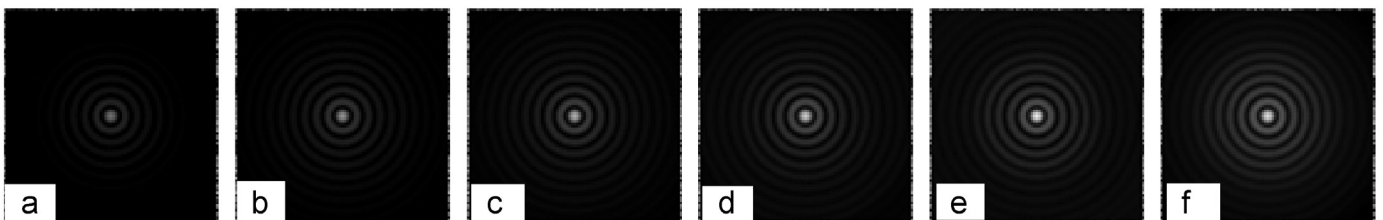


Fig. 3. Intensity distribution of the cross-section of the beam: (a) $z=50$ mm, (b) $z=80$ mm, (c) $z=110$ mm, (d) $z=140$ mm, (e) $z=170$ mm, and (f) $z=200$ mm.

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