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Polychromatic Bessel beams of zero and first orders

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Abstract— **In this paper, we will show that Bessel beams can be created from temporarily incoherent wide-range light sources, including a halogen lamp. In this study, the possibility of forming polychromatic Bessel beams of zero and first orders is shown, an interference pattern is formed**

Keywords— polychromatic Bessel beam, topological charge, topological quadrupole.

I. Introduction

The propagation of invariant light fields, such as Bessel light beams [1,2,3], is of interest in a wide range of current proposals such as micromanipulation, plasma generation using laser radiation, and the study of optical angular momentum. Considering optical fields as a superposition of conical waves, we explore how the coherent property of light plays a key role in their formation. As an example, we will show that Bessel beams can be generated from temporarily incoherent wide range light sources, including a halogen lamp. Using a supercontinuous light source, we will explain how light beams depend on the spectral width function of the incident light field.

II. Theoretical description of polychromatic bessel beams

It is well known that diffraction is the characteristic wave nature of light, which occurs when any wavefront is pointwise modulated in amplitude and/or in phase. The parts of the wavefront that propagate after modulation interfere and diffraction orders arise. From the point of view of quantum mechanics, diffraction is the center of understanding of the Heisenberg uncertainty principle and is directly related to the concept of de Broglie's concept of a particle, which can be assigned a wavelength that is inversely proportional to the moment of the particle. In this regard, solutions to the Helmholtz equation that are propagation invariant or "pseudo-non-diffracting" have gained considerable interest and application in recent years.

First, consider a simple theory of wide-range Bessel beams that describes our observations. In particular, we will consider the propagation of a low-order pulsed Bessel beam through air, for which the chromatic dispersion is negligible. The electric field is described in a scalar slowly varying approximation using the envelope $E(r,z,t)$, where the carrier $exp(i\omega_0(z-ct)/c)$ with the center frequency ω_0 is excluded, and we assume the presence of radial symmetry along the *z* axis. Then the profile of the integrated flux density, with intensity integrated over the pulse time, can be written:

$$F(r,z)=\int_{-\infty}^{\infty}dt\left|E(r,z,t)\right|^2=\int_{-\infty}^{\infty}d\Omega\left|E(r,z,\Omega)\right|^2 \qquad (1)$$

where the Parseval approximation was used, and the spectral resolution of the envelope $E(r,z,\Omega)$ from $E(r,z,t)$ was obtained using Fourier transforms, where Ω describes the frequency detuning from the carrier $\Omega=\omega-\omega_0$. For the described case, the pulse at the input $z=0$ has a collimated Gaussian profile, and we can describe the spectral part of the envelope as

$$E(r,z=0,\Omega)=E_0\sqrt{S(\Omega)e^{\frac{-r^2}{w_0^2}}}\,e^{i\phi(\Omega)} \qquad (2)$$

where w_0 is the size of the Gaussian spot at the input, $S(\Omega)$ is the normalized pulse spectrum, $\Phi(\Omega)$ is the frequency dependent phase, and E_0 is the field amplitude. The incoming field first passes through the axicon, with refractive index n and angle *γ*, and then propagates along the *z* axis. It is well known that the incoming Gaussian beam transforms into a Bessel beam over the propagation length in the vicinity of $z=z_{max}/2$, where $z_{max}=w_0/\theta$ and $\theta=(n-1)\gamma$. Then, the spectrally represented field in the observation plane can be described as

$$E(r,z=z_{max}/2,\Omega)=E_0\sqrt{\mathrm{S}(\Omega)\mathrm{e}^{\mathrm{i}\left(\phi(\Omega)-\frac{\mathrm{kr}^2}{2\mathrm{z}}-\frac{\mathrm{k_r^2\,z}}{2\mathrm{k}}\right)}}\,f(z,\Omega)J_0(k_r(\Omega)r) \qquad (3)$$

where $f(z,\Omega)\approx f(z,0)$ is a slowly varying function of frequency and z is a neighborhood of $zmax/2$ and $k_r(\Omega)=(\omega_0+\Omega)(n-1)\gamma/c$ is the radial component of the wave vector. Substituting the approximate solution for the Bessel beam (3) into (1), we obtain the normalized profile of the integrated flux density

$$F(r)=\frac{F(r,z_{max}/2)}{F_0(z_{max}/2)}=\int_{-\infty}^{\infty}d\Omega S(\Omega)J_0^2(k_r(\Omega)r), \qquad (4)$$

where $F_0\left(\frac{z_{max}}{2}\right)=\left|E_0 f\left(\frac{z_{max}}{2},0\right)\right|^2$. The integral flux profile $F(r)$ in equation (4) must be compared with the experimental integral flux profile for pulsed Bessel beams with different spectra $S(\Omega)$. As a simple model, we consider the Gaussian spectrum:

$$S(\Omega)=\frac{1}{\sqrt{\pi}\,\Delta\omega}e^{\frac{-\Omega^2}{\Delta\omega^2}}, \qquad (5)$$

where $\Delta\omega$ is the pulse width. Note that in formula (4) for the integrated flux density profile, both the spectrum $S(\Omega)$ and the argument of the Bessel function $J_0(kr(\Omega)r)$ depend on Ω, and thus the momentum spectrum affects the profile of the integrated beam flux density. Basically, the fluence profile is the sum over the momentum bandwidth of Bessel beams $J_0(kr(\Omega)r)$, which vary as $cos^2(kr(\Omega)r-\pi/4)=[1+cos(2kr(\Omega)r-\pi/2)]/2$ for $kr(\Omega)r>>1$. With an average pulse passage $\Delta\omega$, oscillations $cos^2(kr(\Omega)r-\pi/4)$ from Bessel beams will be largely canceled along the radii, which π phase difference or more exists between the spectrum edge $\Omega=\Delta\omega$ and at the center $\Omega=0.2(kr(\Delta\omega)-(kr(\Omega))r\geq\pi$, which determines the critical radius π of the phase difference

$$\left(\frac{r_{cr}}{\lambda}\right)=\frac{1}{4(n-1)\gamma(\Delta\omega/\Delta\omega_0)}=\frac{1.67}{4(n-1)\gamma(\Delta\omega_{FWHM}/\omega_0)}, \qquad (6)$$

were $\omega_{FWHM}=2\sqrt{\ln(2)}\Delta\omega$. In other words, the number of Bessel beam rings in white light can be considered as a change in the pulse width $\Delta\omega$. The number of rings can be approximately equal to

$$N_{fr}\approx Int\left(\frac{2k_r(\Omega)r_c-\frac{\pi}{2}}{2\pi}\right)\approx Int\left(\frac{1.67\left(\frac{\Delta\omega_{FWHM}}{\omega}\right)^{-1}-\frac{1}{2}}{2}\right) \qquad (7)$$

III. Generation of zero-order polychromatic bessel beams

At present, after the creation of an axicon or a conical lens, interest in the study of Bessel-Gaussian beams obtained on an axicon has greatly increased. At present, the properties of this class of beams for monochromatic radiation are well studied. However, when generating Bessel-Gaussian beams, a number of difficulties arise.

An experimental setup was created to generate polychromatic zero-order Bessel beams. The light from a high-pressure xenon lamp was focused by a mirror-lens condenser and a 20x microobjective onto the input end of an optical fiber [4,5] with a core diameter of 7.5 µm and a cladding diameter of 27.5 µm.

The need to use an optical fiber arose due to the fact that the light from a xenon lamp is not coherent, and a coherent light source is needed to generate a Bessel beam [4]. Various types of optical fibers have been studied to create this type of source with core diameters from 4 to 120 µm. If we take a fiber with a large core diameter, then the intensity of the light flux is sufficient for generation, but the Bessel beam pattern itself looks blurred or disappears altogether due to the small coherence length. If we take a fiber with a small core diameter, then as a result we will get a sufficiently contrasting Bessel beam, but the intensity of this picture does not allow us to fix the image we need.

After the passage of light in the fiber, we collimated the radiation at the output using a 10x microobjective. The beam after collimation had a diameter of 5 mm. Subsequently, our beam was directed to a conical lens—an axicon.

We projected the stretched focal zone after the axicon with an 8x microobjective onto a CCD matrix - cameras.

IV. Generation of first-order polychromatic bessel beams

We were faced with the problem of obtaining a Bessel-Gaussian beam of the first order. In this beam, a single optical vortex with a topological charge $l=1$ is located on the axis. Therefore, to obtain a first-order Bessel-Gaussian beam, it is necessary to generate an optical vortex in polychromatic light. For this purpose, we used the conoscopic picture, which is obtained on a uniaxial crystal [6-8] placed between two parallel polarizers. The view of the theoretically calculated intensity distribution pattern is presented on the next slide.

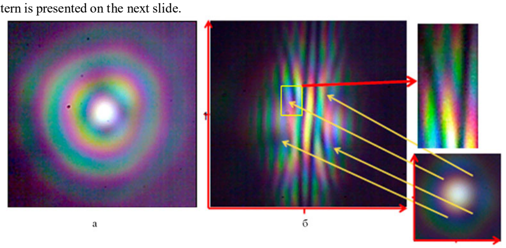

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Fig. 1. Zero order Bessel-Gauss beam (a) and its interference pattern (b).

As can be seen from Fig. 1, a quadrupole consisting of single optical vortices is formed in the central part. Therefore, if the optical axis of the beam is directed along the direction of one of the vortices, then after the output polarizer we will get a beam with an optical vortex on the axis.

To generate polychromatic zero-order Bessel beams, the experimental setup for generating polychromatic zero-order Bessel beams was improved. Light from a high-pressure xenon lamp was directed to an optical fiber with a core diameter of 7.5 µm and a cladding diameter of 27.5 µm using a lens condenser and a 20x microobjective.

After the passage of light in the fiber, we collimated the radiation at the output using a 20x microobjective.

Subsequently, we directed our beam to a conical lens, the axicon. We projected the stretched focal zone after the axicon with a 10x microobjective onto the input face of a uniaxial crystal to generate a polychromatic vortex with a topological charge $l=1$. But to generate a "white" polychromatic vortex, it is necessary that a linearly polarized beam hit the anisotropic crystal. To do this, a polarizing filter was placed between the projecting microobjective and the anisotropic crystal, which transformed the beam into a beam with linear polarization. Later, after the anisotropic crystal, the beam passed through the second polarizing filter and hit the matrix of the CCD camera.

As we said, obtaining an interference pattern is possible only if the interference waves are coherent with each other. In our experimental setup, to generate polychromatic zero-order Bessel beams, we used a xenon lamp, which has a very small coherence length, and although we used an optical fiber as a point source to increase the coherence length, obtaining classical interference was very difficult. Therefore, to obtain an interference pattern, we used the Fresnel biprism.

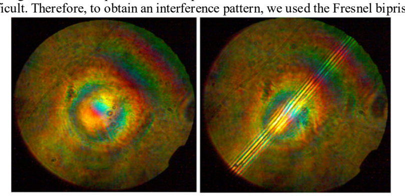

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Fig. 2. Beam of the Bessel-Gauss of the first order (a) and its interference pattern (b)

Figure 2 shows the interference pattern of first-order polychromatic Bessel beams. When considering the interference pattern, one can clearly see the presence of a colored fork, the position of which coincides with the position of the minimum on the beam axis. This indicates that our assumptions about the presence of an optical vortex on the beam axis were confirmed. Also in the interference pattern there are paired opposite forks, the location of which corresponds to the position of the original quadrupole of the Bessel-Gaussian beam.

We compared the properties of non-diffracting light fields created using different light sources. In this study, the possibility of forming polychromatic Bessel beams of zero and first orders is shown, an interference pattern is formed. The resulting interference pattern (Fig. 2) is a regular interference fringes near the axis. This indicates that there is a smooth wave front at the center of the beam. However, the dark bands are irregular. This can be seen from the distortion of the picture, forks appear. In general, forks in the interference pattern correspond to optical vortices carried by the beam. The presence of forks corresponds to a topological quadrupole, and its occurrence is associated with aberrations caused by inaccuracies in lens manufacturing. The orientation of the plugs corresponds to the sign of the charge. The top and bottom charges are the same but opposite in sign. This method can be used to study the spin and orbital angular momentum based on the intensity moments both in in inhomogeneous media [6-8], free space [9,13], as well as for studies of fractional topological charges [14,15].

In this work, we have shown that Bessel beams can be created from temporarily incoherent wide-range light sources, including a halogen lamp. In this study, the possibility of forming polychromatic Bessel beams of zero and first orders is shown, an interference pattern is formed.

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References

1. G. J. Gbur, "Singular optics," New York: CRC Press, 2017. ISBN: 978-1-4665-8077-0
2. V.V. Kotlyar, A.A. Kovalev, A.P. Porfirev, "Vortex Laser Beams," New York: Taylor & Francis Groop, 2019. ISBN: 978-1-138-54211-2.
3. D. McGloin, K. Dholakia, "Bessel beams: diffraction in a new light," Contemporary Physics, vol. 46, pp. 15–28, 2005. DOI: 10.1080/0010751042000275259
4. Fischer P. White light propagation invariant beams / P. Fischer, C.T.A. Brown, J.E. Morris, C. López-Mariscal, E.M. Wright, W. Sibbett and K. Dholakia // Optics Express, - 2005, - Vol. 13(17). - P.6657. DOI: 10.1364/OPEX.13.006657
5. Nye J.F. Natural Focusing and Fine Structure of Light. Caustics and Wave Dislocations / Bristol and Philadelphia: Institute of Physics Publishing., 1999. - 327 p. DOI: 10.1119/1.19543
6. T. Fadeyeva, Yu. Egorov, A. Rubass, G. A. Swartzlander, A. Volyar, "Indistinguishability limit for off-axis vortex beams in uniaxial crystals," Optics Letters, vol. 32(21), pp. 3116–3118, 2007. DOI: 10.1364/OL.32.003116
7. A.V. Volyar, T.A Fadeeva, Y.A. Egorov, "Vector singularities of Gaussian beams in uniaxial crystals: Optical vortex generation," Technical Physics Letters, vol. 28(11), pp. 958–961, 2002. DOI: 10.1134/1.1526896
8. A.V. Volyar, Y.A. Egorov, A. Rubass, T.A. Fadeeva, "Fine structure of white optical vortices in crystals," Technical Physics Letters, vol. 30(8), pp. 701–704, 2004. DOI: 10.1134/1.1792318
9. A.V. Volyar, M.V.Bretsko, Y.E. Akimova, Y.A. Egorov, "Shaping and processing the vortex spectra of singular beams with anomalous orbital angular momentum," Comp. Optics, vol. 43(4), pp. 517–527, 2019. DOI: 10.18287/2412-6179-2019-43-4-517-527
10. A.V. Volyar, E. Abramochkin Y.A. Egorov, M.V. Bretsko, Y.E. Akimova, "Fine structure of perturbed Laguerre–Gaussian beams: Hermite–Gaussian mode spectra and topological charge," Applied Optics, vol. 59(25), pp. 7680–7687, 2020. DOI: 10.1364/ao.396557
11. A.V. Volyar, M.V. Bretsko, Y.E. Akimova, Y. A. Egorov, "Digital sorting perturbed Laguerre-Gaussian beams by radial numbers" JOSA A, vol. 37(6), pp. 959–968, 2020. DOI:10.1364/josaa.391153
12. A.V. Volyar, M.V. Bretsko, Y.E. Akimova, Y.A. Egorov, "Orbital angular momentum and informational entropy in perturbed vortex beams," Opt. Lett., vol. 44(23), pp. 5687–5690, 2019. DOI: 10.1364/OL.44.005687
13. A.V. Volyar, M.V. Bretsko, Y.E. Akimova, Yu. A. Egorov, "Sectorial perturbation of vortex beams: Shannon entropy, orbital angular momentum and topological charge," Computer Optics, vol. 43(5), pp. 723–734, 2019. DOI: 10.18287/2412-6179-2019-43-5-723-734
14. V. Volyar, Yu. Egorov, "Super pulses of orbital angular momentum in fractional-order spiroid vortex beams," Opt. Lett, vol. 43, pp. 74, 2018. DOI:10.1364/OL.43.000074
15. C.N. Alexeyev, Y.A. Egorov, A.V. Volyar, "Mutual transformations of fractional-order and integer-order optical vortices," Phys Rev A, vol. 96, pp. 063807, 2017. DOI: 10.1103/PhysRevA.96.063807.