Demonstration of Generalized higher-order Bessel-Gauss beam solutions in optical resonators

D. N. Schimpf,[1,2] J. Schulte,[2] W. P. Putnam,[2] and F. X. Kärtner[1,2]

[1]*Center for Free-Electron Laser Science, DESY and Department of Physics, University of Hamburg, Notkestrasse 85, Hamburg 22607, Germany*
[2]*Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, Massachusetts 02139, USA*
Author e-mail address: dschimpf@cfel.de

Abstract: We propose azimuthally symmetric higher-order Bessel-Gauss beams, and experimentally demonstrate them as higher-order eigenmodes in optical resonators comprising aspheric mirrors

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1. Introduction

Bessel-Gauss beams offer a variety of properties not provided by conventional Gaussian beams. Resonators for such beams utilize the attributes of these beams intra cavity. Specifically, Bessel-Gauss beams have recently been proposed as operating modes for enhancement cavities, which are employed in strong-field physics experiments such as cavity-enhanced high-harmonic generation [1]. The advantages of Bessel-Gauss beams include near-perfect out-coupling of the generated intra-cavity high-harmonics and an increased intensity ratio from the focus to the cavity mirror surfaces. The fundamental operating mode in such resonators is the well-known Bessel-Gauss beam. By numerically solving for the modes in these resonators, we also find higher order modes in such resonators. While the fundamental and azimuthally varying higher-order Bessel-Gauss beams are well known, to the best of our knowledge, the azimuthally symmetric Bessel-Gauss beam solutions have not been reported in the literature until now.

In this contribution, we propose and experimentally demonstrate a class of higher-order Bessel-Gauss beams that constitute hitherto unknown beam solutions. Analytical expressions are presented for these beams, and we experimentally demonstrate these beams by exciting modes in optical resonators comprising aspheric optics. These beams show a number of exciting attributes that can be exploited, e.g., for frequency conversion of laser radiation.

2. Generalized higher-order Bessel-Gauss beam solutions

To describe these modes analytically, we generalize the analysis employed for conventional Bessel-Gauss beams [2]. Specifically, we compose higher-order Bessel-Gauss beams in an intuitive way by superposing decentered Hermite-Gaussian beams, whose centers are positioned on a circle and whose beam directions are pointing to the apex of a cone, as displayed in Fig. 1(a).

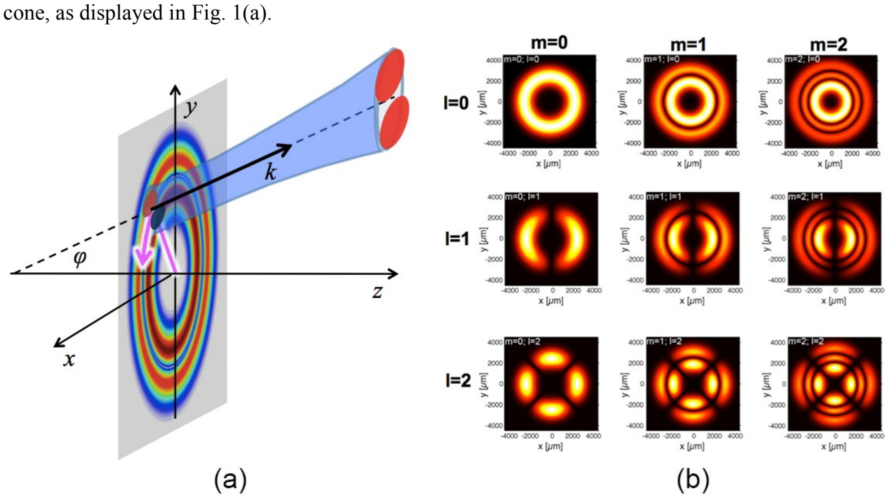

Fig 1: (a) Superposition of generalized decentered Hermite-Gaussian beams. (b) Transverse beam pattern of Bessel-Gauss beams.

The resulting generalized higher-order Bessel-Gauss beams can be written as

$$U_{BG}^{ml}(r,\phi,z) = A\cdot\exp(-im\phi)\cdot\exp\left(i\frac{k}{2q}(r^2+r_d^2)\right)\cdot\mathscr{I}_{ml}(r,z) \quad (1)$$

Where I_{ml} can be written as a sum of Bessel functions. The transverse beam patterns of the generalized higher-order Bessel-Gauss beams are shown in Fig 1(b). It can be seen that with increasing radial index m, more nodes appear within the annulus in the radial direction. Also, with increasing angular index l, more azimuthal variations are present. Since these beams were built from decentered component beams, the transformation of these higher order Bessel-Gauss beams through ABCD optical systems is readily described. Another interesting feature of these beams is that they encompass the Laguerre-Gaussian beams as a special case.

In Fig. 2, we show the propagation of the fundamental, as well as higher-order azimuthally symmetric Bessel-Gauss beams through the geometrical focus, i.e. the region around the apex of the cone. For the higher-order Bessel-Gauss beams the amplitude variation on the annulus maps into an on-axis intensity variation. This feature can be used for quasi-phase matching of nonlinear processes.

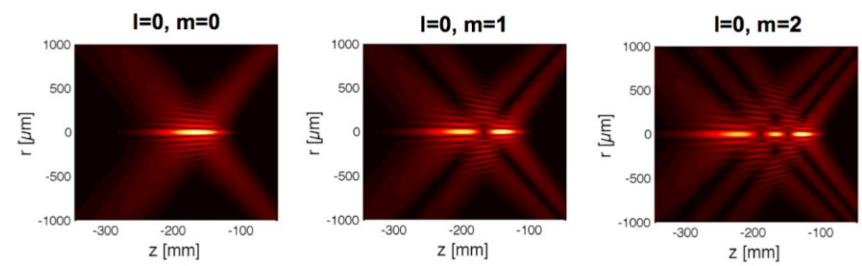

Fig 2: (a) Amplitude of generalized decentered Bessel-Gauss beams vs propagation distance for increasing mode order m.

3. Experiment

To confirm the practical relevance of these higher-order Bessel-Gauss beams, consider the resonator configuration as shown in Fig. 3(a). It comprises an axicon mirror (base angle ε = 0.5°) and a spherical mirror (radius of curvature R = 250 mm). For the design of the experiment we chose a separation distance of L= 78 mm resulting in a fundamental Bessel-Gauss mode with a ring radius of 1.5 mm and an annulus waist of ~200 µm at the axicon mirror for a wavelength of 1040 nm.

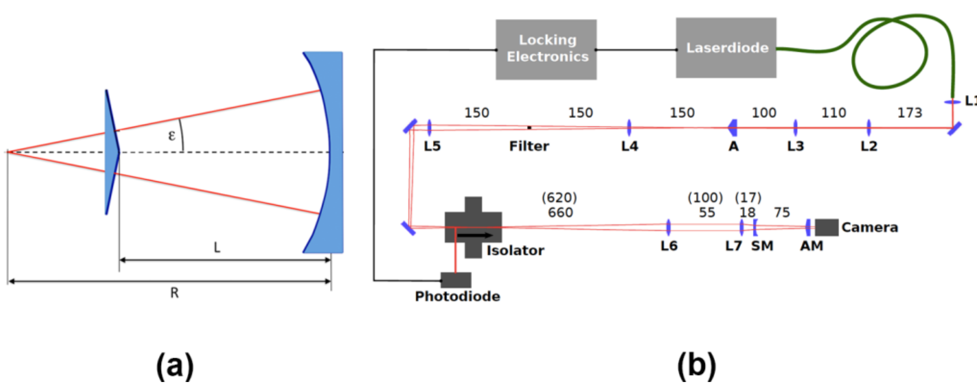

Fig 3: (a) Schematic of the Bessel-Gauss beam resonator (b) complete experimental setup.

The schematic of the complete experimental setup is shown in Fig. 3(b). The Gaussian beam output of a fiber-pig tailed diode laser (with a wavelength of about 1040 nm) illuminates an axicon. The resulting ring beam is mode-matched to the resonator. The laser is a single frequency laser, and its wavelength can be tuned by a piezoelectric element. This allows us to lock the laser frequency (with a line width of about 100 kHz) to the resonance of the enhancement cavity by dither locking. The light reflected from the front surface of the spherical input coupler is used as a feedback signal for the locking loop. As shown in Fig. 4, the leakage through the axicon mirror is used to record the resonator modes with a camera, which is placed behind this mirror. These images of the resonator modes were taken at a distance z= 25 mm behind the flat surface of the axicon mirror. In Fig 4 we also compare the experimental data to numerical simulations that are based on the analytical expressions. The evolution of the beam profile as a function of other distances from the axicon mirror is similar to the one shown in Fig. 2. In Fig.4 azimuthal variations of the intensity on the annulus can be seen, which are due to surface imperfections of the resonator mirrors [1].

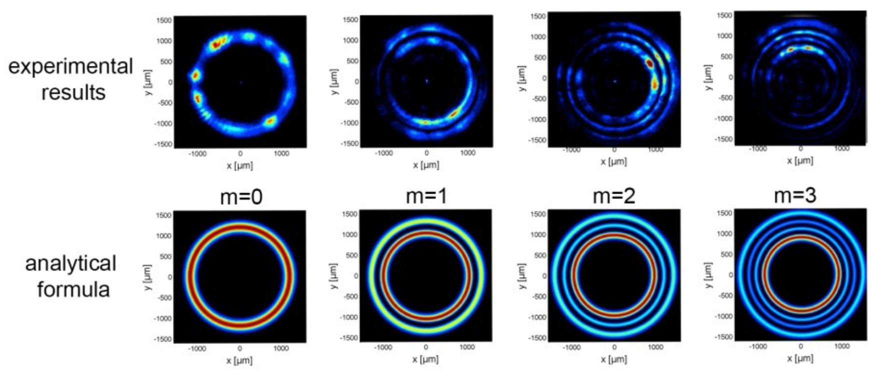

Fig 2: Comparison of experimental resonator modes and the analytical solution for the azimuthally symmetric higher-order Bessel-Gauss beams.

4. Conclusion

In this work, Bessel-Gauss beams have been extended by introducing a set of higher-order solutions. We derive analytical expressions for these beams by superposing decentered Hermite-Gaussian beams on a circle, and find that the well-known Bessel-Gauss beam is the fundamental solution of this class. We can show that the new class of higher-order Bessel-Gauss modes encompass Laguerre-Gaussian beams. The practical relevance of these beams for Bessel-Gauss beam resonators is demonstrated by exciting these modes in optical resonators consisting of aspheric mirrors. These generalized Bessel-Gauss beam solutions offer new interesting attributes such as an on-axis intensity modulation. This can be utilized for laser applications such as laser-matter interactions, quasi-phase matching of nonlinear processes, or mirco particle trapping and manipulation [3].

Kommentar [PK1]: Not clear what you mean here

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