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BESSEL BEAM PARAMETER OPTIMIZATION WITH ADJUSTABLE ABERRATOR

Abstract. Transformation of ordinary laser beams of Gaussian type into the ones of Bessel type gives a number of advantages. In particular, it may improve a multi-mode beam energy distribution in the far zone and keep it stable over a long range of propagation distances. A usual method of the Bessel beam formation is based on the use of one or a pair of axicons, at that the latter is used for creating annular beams with small conic angles optimized for long range propagation. The disadvantage of axicons is their fixed geometry not allowing the beam parameter adjustment. An additional Bessel beam improvement allowing to reach a finer energy distribution comes from injection into it a controllable amount of spherical aberration. This requires development of a specialized optical system, which adds adjustable spherical aberration to the laser beam. Efficient design of such an optical system has been created and experimentally tested on the transformation of a multi-mode laser beam into Bessel beam.

Keywords: Bessel-like beam, aberrator, far zone, multimode beam, spherical aberration

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ОПТИМИЗАЦИЯ ПАРАМЕТРОВ БЕССЕЛЕВЫХ ПУЧКОВ С ИСПОЛЬЗОВАНИЕМ ПЕРЕСТРАИВАЕМОГО АБЕРРАТОРА

Аннотация. Преобразование классических лазерных пучков в пучки бесселева типа имеет ряд преимуществ. В частности, оно может улучшить распределение энергии в дальней зоне для многомодового пучка и стабилизировать это распределение в широком диапазоне дистанций. В стандартном методе формирования бесселева пучка с применением одного или двух аксиконов последние используются для создания кольцевых пучков с малым углом конуса, оптимизированных для распространения на большие дистанции. Недостатком аксиконов является их фиксированная геометрия, не позволяющая настраивать параметры пучка. Дополнительное улучшение для структуры пучков бесселева типа, позволяющее реализовать более точные распределения энергии, достигается за счет добавления в пучок контролируемого количества сферической аберрации. Это требует разработки специализированной оптической системы, которая добавляет управляемую сферическую аберрацию в лазерный пучок. Эффективная конструкция подобной оптической системы предложена и экспериментально реализована применительно к преобразованию многомодовых лазерных пучков в пучки бесселева типа.

Ключевые слова: пучки бесселева типа, аберратор, дальняя зона, многомодовый пучок, сферическая аберрация

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Introduction. Long-range free-space propagation of laser beams are employed in a number of important applications: the Optical Free-Space Communication, Laser Imaging, Detection And Ranging (LIDAR), laser targeting, etc. The problem of suppressing the diffraction effects as well as the atmospheric turbulence beam corruption along the long propagation distances can be reasonably well mitigated by the transformation of the traditional Gaussian or Laguerre-Gaussian multi-mode laser beams into the specialized quasi-nondiffractive beams of Bessel type. The Bessel type beams aimed to diffraction suppression over the long-range propagation were suggested in [1], where the combination of defocus and spherical aberration was used to generate a nondiffracting Bessel-like beam, and in [2], where for the same purpose an annular Bessel-like beam was generated using a two-axicon optical

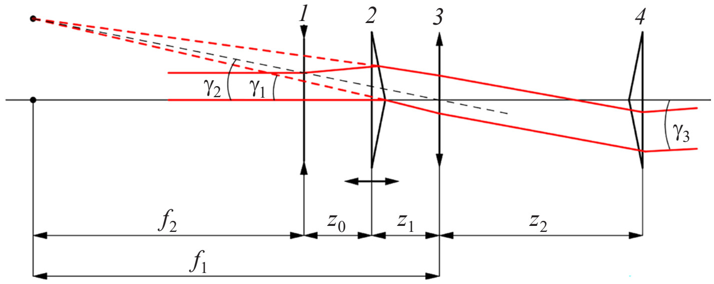

Fig. 1. The thin-component optical scheme of the adjustable 2-axicon telescope beam forming system based on a Galilei telescope. The axicon telescope is formed by two positive axicons (components *2* and *4*) with equal conic angles. In order to adjust the exit cone angle the first axicon is surrounded with the negative and positive lenses with common focus (components *1* and *3*). The exit beam cone angle is zero if the first axicon (component *2*) is put at zero distance z1 from the positive lens (component *3*). If this distance increases, the exit cone angle Y increases towards the axis

scheme. In both cases the main goal is to generate a conical wavefront with very small cone angle, which is a typical requirement for the long-range propagation. There exists, however, a longstanding problem of fine tuning of the beam parameters such as the cone angle, for which a couple of known solutions are available. First one is to use an "augmented" axicon telescope [3] by adding to it a pair of lenses that make an afocal system as it is shown in Fig. 1. Moving along the optical axis an axicon located between the lenses and illuminated with a nonparallel beam allows changing the cone angle.

An alternative approach is based on the observation that a combination of defocus and spherical aberration approximates quite well a conical wavefront [1], which opens a way to correct the cone angle in a Bessel beam by a purely lens-based optical system. It is strongly desirable, however, to be able to smoothly adjust the amount of conic phase introduced into a beam, which implies the need to control both defocus, which is easy, and spherical aberration, which is less trivial. As it was suggested in [4], it is also desirable to introduce some extra amount of spherical aberration, not for the conical wavefront approximation but for additional fine correction of the beam energy distribution. Numerical simulations of the beam transformation and propagation using, for instance, the Generalized Fresnel Integral approach [5] can be a simple and physically reproducible way to find the optimal parameters, such as defocus and amount of spherical aberration, of the Bessel beam formation optical system. However, when working with the real lasers with unknown mode structure, especially multi-mode lasers, it is nearly impossible to get the correct initial laser beam parameters that could guarantee the practically reproducible simulation result. It is more reliable and simple to perform a physical experiment on a real laser to find the optimal Bessel beam formation system parameters by direct trial and error. This experiment requires a tunable aberration generating optical system allowing to change the required parameters, basically the defocus and spherical aberration, within certain range. The present paper is devoted to the solution of this problem, namely, development and creation of adjustable aberration optical system and its experimental testing on multimode laser into a Bessel beam transformation.

1. Design of optical aberrator system. A simple design solution for such an optical system, which we will call an "aberrator", is shown and explained in Fig. 2. By two adjustments: the negative lens and the meniscus axial motions, we can (almost) independently control the amount of defocus and spherical aberration, respectively. In order to introduce a desirable amount of the conic phase, one needs to know an "adjustment function" $\alpha = f(\delta l, \delta m)$, where α is the Bessel beam wavefront conic angle, δl, δm are the values of the negative lens and the meniscus axial motions w.r.t. some initial positions. The latter function can be easily computed by ray tracing analysis of the aberrator optical system, which will be presented below.

A tunable aberrator type optical system for the Bessel beam adjustment has certain practical advantages:

– the cone angle adjustment is done by lens instead of axicon motions, which is more desirable because axicons are more sensitive to misalignments;

– there is a possibility to introduce independently some amount of spherical aberration/defocus in excess to what is necessary for creating a conic phase, a property absent in the adjustable axicon telescope presented in Fig. 1;

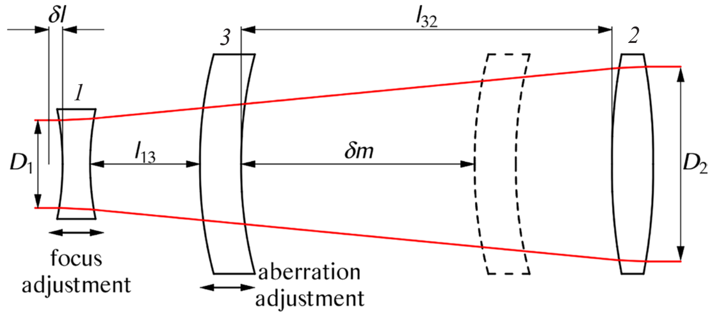

Fig. 2. The 3-component adjustable aberrator optical system. Components *1* and *2* make a usual Galilei telescope. Component *3* is a Maksutov meniscus, a lens with zero optical power, introducing spherical aberration due to its surfaces being non-confocal to the incident light beam. Axial movement of the meniscus inside the diverging beam created by the negative component 1 allows to change the diameter of the beam spot on the meniscus, thus, changing the amount of spherical aberration it introduces with nearly no change in the overall system optical power

– given an ample range of the aberration adjustment, an aberrator system becomes a useful universal laboratory functional module attachable to various optical devices.

2. Aberrator optical calculations. In this section we describe the optical design calculations for the aberrator optical system. The system was designed in the context of a broader task, namely, to carry out an experiment aiming to improve long-range propagation properties of a multi-mode laser beam by transforming it into a Bessel-like beam with injected spherical aberration. The purpose of the aberrator in this experiment was to introduce a variable amount of defocus and spherical aberration into an annular beam created by a 2-axicon telescope as a first stage of the laser beam transformation, see Fig. 3.

Requirements for the aberrator optical system design are dictated by the parameters of the existing axicon telescope and the multi-mode laser to work with. Table 1 summarizes the aberrator design requirements.

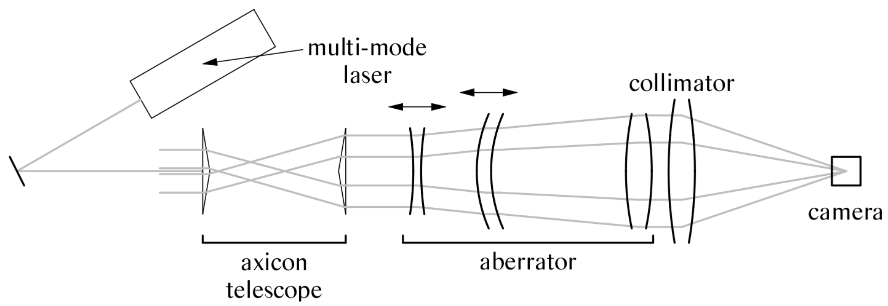

Fig. 3. The scheme of an experiment with a real multimode laser and the Bessel beam formation system equipped with the adjustable aberrator. The axicon telescope made of two identical axicons is used to create an annular beam. The aberrator adds the defocus and spherical aberration. The collimator makes Fourier transform allowing the camera being located near the collimator focus to register the beam intensity distribution in the far zone at the distances equivalent to long-range propagation

Table 1. **Requirements for the aberrator optical system design**

Parameter	Value	Unit
Working wavelength	1.064	[μm]
Input beam	12	[mm]
Output beam	30	[mm]
Cone angle range	$\pm 3 \cdot 10^{-4}$	[rad]
Spherical aberration at extremes	300	[nm] Peak to Value
Meniscus adjustment range	50	[mm]
Meniscus gap at extremes	≥5	[mm]
Overall optical power	0	[mm–1]

The optical calculation process has the following peculiarities:

– Since the cone angle is a combination of defocus and spherical aberration, the necessary range of spherical aberration to get the specified cone angle range is found by trial and error.

– The meniscus orientation can be chosen with its convex side turned either to the negative or to the positive lens. The former turns out to be preferable, as it results in larger ray angles on the meniscus and, thus, larger range of spherical aberration adjustment within the meniscus travel between the negative and positive lenses.

– At the start of calculation process one fixes the meniscus initial position and specifies the amount of spherical aberration in the exit pupil for this position. Then it is necessary to optimize the entire system to obtain the specified amount of the aberration. We fix the following parameters: i) the lens thicknesses $d_{1,2,3}$, ii) the system magnification D_2/D_1 in pupils for the meniscus at the initial position, iii) the zero optical power $p_3 = 0$ of the meniscus.

The following is left as fixed parameters optimized by trial and error: i) the choice of lens glasses, ii) the positive lens power p_2, iii) the meniscus first surface curvature r_1^3.

The following parameters are bound by the constraints:

i) the negative lens power p_1 given powers of the other two lenses and the magnification D_2/D_1 in pupils,

ii) second radii $r_1^{1,2,3}$ of all three lenses given the first ones and the lens powers.

Two parameters: first radii $r_1^{1,2}$ of the negative and positive lenses are left free for optimization to reach the specified aberration value.

– Once optimization for the specified aberration at the meniscus initial position is finished, the meniscus is set into its final position and the resulted aberration is calculated. If it does not reach the desired value, the free parameter values are manually changed and the optimization is repeated. Usually, it is desired that the aberration at the meniscus final position was equal to that at the initial position but with the opposite sign (an implicit "symmetry constraint"). If it proves to be impossible to obtain the symmetric value of the final aberration, it would be a good idea to specify a different sign of the initial aberration.

Mathematically, the process of the constraint application is the following:

1. Decide on glasses for all components, their corresponding refractive indexes $n_{1,2,3}$ and the component thicknesses $d_{1,2,3}$.

2. Set the first meniscus radius r_1^3 and compute its second radius given the zero optical power p_3:

$$r_2^3 = \frac{1-n_3}{m_{21}n_3} m_{11}, \qquad m = \begin{bmatrix} 1 & d_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{1-n_3}{r_1^2} & \dfrac{1}{n_3} \end{bmatrix}, \tag{1}$$

where m is the ABCD-matrix of propagation through the meniscus first and up to the second surface.

3. Take the positive lens first radius r_2 from the probing glass list. Compute

$$r_2^2 = \frac{1-n_2}{m_{21}n_2 + p_2} m_{11}, \qquad m = \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{1-n_2}{r_1^2} & \dfrac{1}{n_2} \end{bmatrix}, \tag{2}$$

where m is the ABCD-matrix of propagation through positive lens first and up to the second surface, n_2, p_2 are the positive lens refractive index and the prescribed optical power. Round $r_2^{2,3}$ to the probing glass list radii.

4. Find ABCD-matrices $m^{2,3}$ for the positive lens and meniscus. With the specified distance l_{32} between the meniscus in its initial position and the positive lens find the ABCD-matrix

$$m^{23} = m^2 \begin{bmatrix} 1 & l_{32} \\ 0 & 1 \end{bmatrix} m^3 \tag{3}$$

of the (meniscus, positive lens) pair.

5. Compute the negative lens optical power:

$$p_1 = m_{21}^{32} D_2 / D_1. \tag{4}$$

6. Analogously to (2), given the negative lens first radius r_1^1 and power p_1 find r_2^1. Round r_2^1 to a probing glass list radius.

7. Find distance l_{13} between the negative lens and meniscus ensuring the afocal propagation:

$$l_{13} = -\frac{b_0 + a_0 / z'}{b_1 + a_1 / z'}, \quad \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = \vec{F}(0,z), \quad \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \vec{F}(1,z) - \begin{bmatrix} a_0 \\ b_0 \end{bmatrix}, \tag{5}$$

$$\vec{F}(l,z) = m^{32} \begin{bmatrix} 1 & l_{13} \\ 0 & 1 \end{bmatrix} m^1 \begin{bmatrix} 1 \\ 1/z \end{bmatrix},$$

where $z, z' = \pm\infty$ are the object and image distances in front and behind the aberrator system.

Because of only two free parameters, one can do a global optimization just scanning through the entire set of available probing glass radii for all allowed $r_1^{1,2}$-pairs to reach a specified value of aberration in the exit pupil.

The result of the optimization process described above is the system with parameters presented in Table 2, the optical scheme and the aberrations in the initial position are given in Fig. 4.

Table 2. **Aberrator system parameters optimized to the requirements given in Table 1, given for the initial meniscus position**

Radius, mm	Thickness, mm	Material
–83.18	5	TF1
39.08	6.377	Air
59.98	7	K8
57.41	45	Air
–250.0	7	TF1
–50.70		

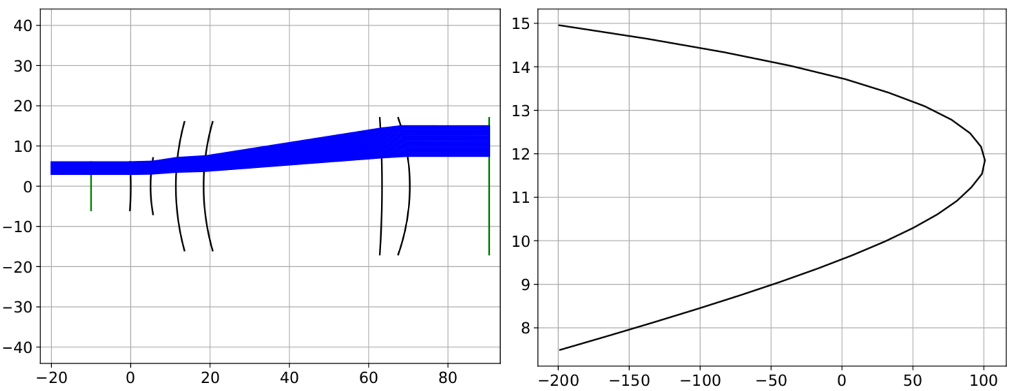

Fig. 4. Left: the optical scheme [in mm] of the optimized aberrator system at the initial meniscus position. Right: the Optical Path Difference [in nm] in the exit pupil at the initial meniscus position

3. Aberrator adjustment function calculation. Once the aberrator design is finished, its analysis is performed in order to figure out how to work with it, namely:

– Can the aberrator system generate an approximation to the conical wavefront phase, in what range and with what approximation error?

– What exactly are the meniscus and negative lens positions that will generate a given value of conical phase correction, i.e. what is the adjustment function $f(\delta l, \delta m)$?

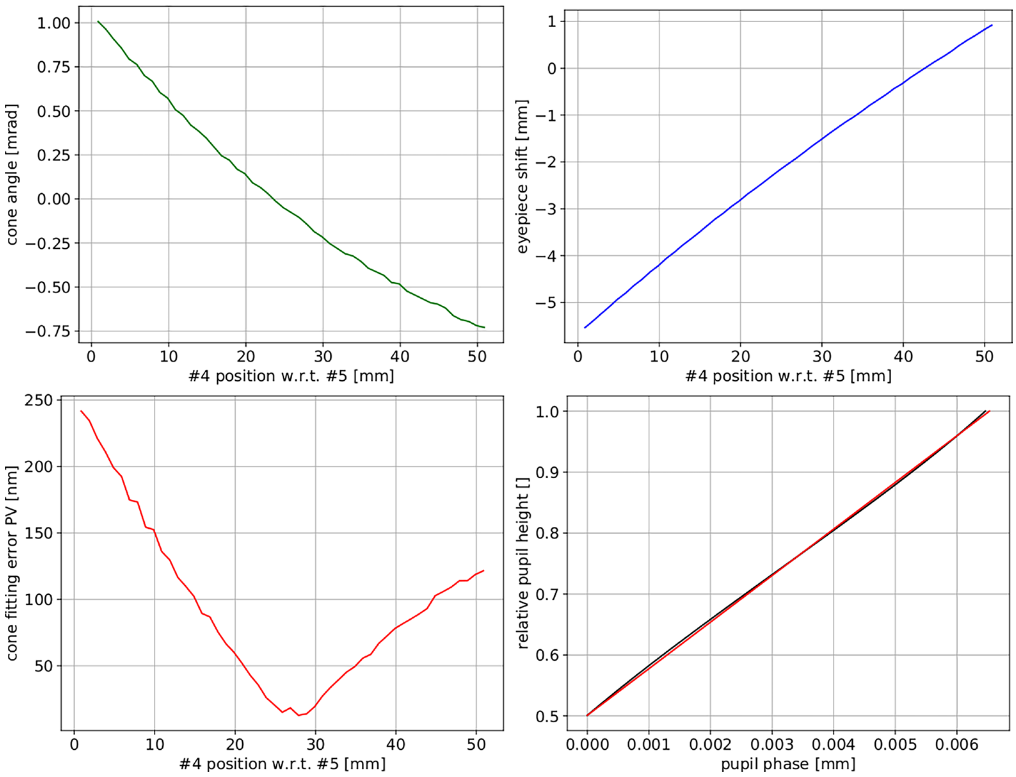

Fig. 5. Results of the adjustment function calculations. Upper row: $\bar{\alpha}(l_{32})$ (left) and $\overline{\delta l}(l_{32})$ (right). Lower row: $\max_x \|\phi(r) - \bar{\alpha}r\|(l_{32})$ (left) and the worst case graph of the OPD approximation by an optimal aberrator phase at the initial meniscus position

A key element of the adjustment function computation is an auxiliary optimization algorithm finding the best approximation to a conical phase with a combination of defocus and spherical aberration. In the aberrator system context this means: given a meniscus position l_{32} (responsible mainly for the spherical aberration value), find a negative lens position δl (responsible mainly for the defocus) such that the optical path difference (OPD) in the exit pupil best approximated a conical phase function. This can be formulated mathematically as two simple one-dimensional optimization problems

$$\overline{\delta l} = \arg\min_{\delta l} \left\|\phi(l_{32}, \delta l, r) - \bar{\alpha} r\right\|^2, \qquad (6)$$

$$\bar{\alpha} = \arg\min_{\alpha} \left\|\phi(l_{32}, \delta l, r) - \alpha r\right\|^2 = \frac{r^{\mathrm{T}}\phi(l_{32}, \delta l, r)}{r^{\mathrm{T}} r},$$

where α is the cone angle, l_{32} is the meniscus position w.r.t. the positive lens (see Fig. 2), δl_1 is the negative lens shift from its initial position, $\phi(l_{32}, \delta l_1, r)$ is the vector of OPD values in the exit pupil as a function of the pupil radial coordinate vector r depending on the meniscus and negative lens positions. It is also assumed that the OPD is piston-removed such that $\phi(0) = 0$. The one-dimensional optimization problem (6) is solved for $\overline{\delta l}$ by a bisection method for a set of l_{32} values. This optimization results are presented in Fig. 5.

The graphs of Fig. 5 can serve as a guide for the aberrator system adjustment for the desired cone angle correction. Also, it is seen that at approximately 23 mm meniscus position w.r.t. the positive lens the aberrator has nearly zero aberrations, which can serve as a starting point for the work on Bessel beam fine shaping.

4. Optimal configuration. The aberrator optical system designed as described in Section 2 had been manufactured and used in the experimental multi-mode Bessel beam optimization shown in Fig. 3. The optimal positions of the aberrator lenses and the optimal far zone intensity profile are presented in Fig. 6. The ray tracing result corresponding to this configuration is shown in Fig. 7. Note that the OPD shape is remarkably close to a cone!

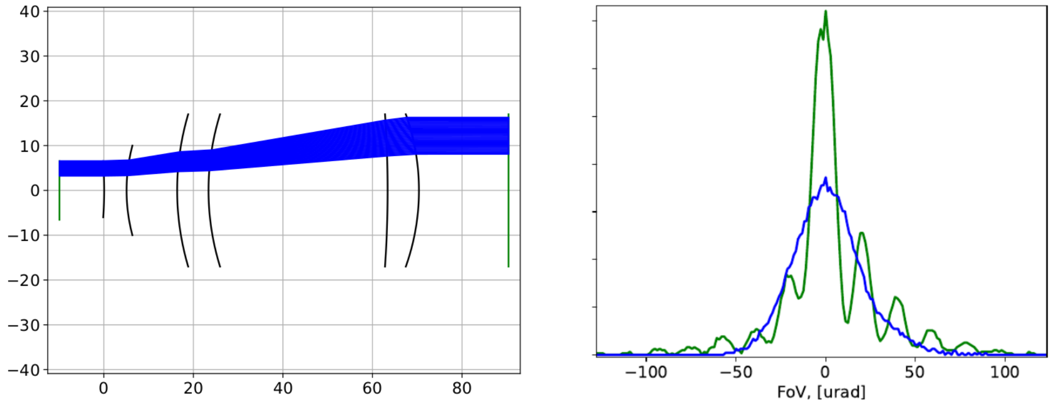

Fig. 6. Aberrator system configuration corresponding to the optimum found in the Bessel beam optimization experiment. Left, the optimal lens position: surface #4–#5 distance is 40.0 mm, surface #2–#5 distance is 58.3 mm, entrance beam 0 is 13.1 mm. Right, the far zone intensity distribution comparison: green is the optimized Bessel-type beam, blue is the classical multi-mode laser beam. The image scales and intensities are normalized to take into account the differences between Bessel and classical beam diameters

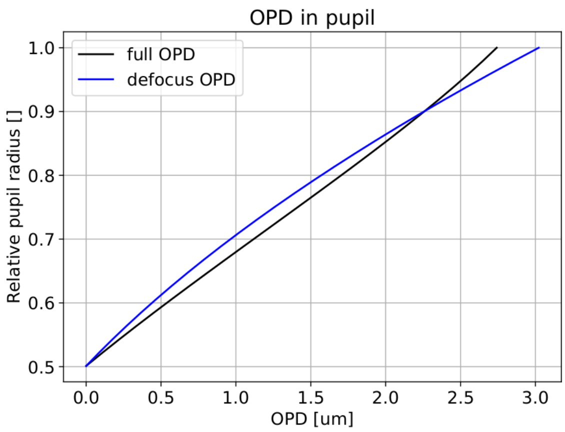

Fig. 7. OPD in the exit pupil of the aberrator in the optimal configuration

The result of the aberrator experiment can be easily transferred to a fixed optical design, for instance, a simple 2-lens Galilei-type beam expander optimized in such a way that the exit pupil OPD map in relative pupil coordinates were the same as that for the aberrator optimal configuration regardless the desired exit beam diameter. Such a fixed optical design was also manufactured and successfully tested with the same laser just showing correctness of the suggested approach.

Conclusion. A novel method for formation of Bessel-like beams with an adjustable cone angle is proposed. The method is based on the use of three-component optical system consisting of a Maksutov meniscus situated inside the Galilei telescope. At the input of the optical system an annular beam is given and the cone angle adjusting of the formed Bessel beam is made by a longitudinal moving of the meniscus and a negative lens. The optimization of the optical scheme is conducted with the purpose of forming a conical phase front at the output beam. The typical cone angle of the Bessel beam is the value of about 1 mrad, and that is why this scheme allows forming Bessel beams with a small number of lateral rings at large distances. Such beams are perspective for laser location, optical communication in free space and also for atmosphere probing.

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