Lasers in Manufacturing Conference 2017

Compact and ultra-flexible gauss to top-hat beam shaping with aspheres

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Abstract

Two refractive beam shaping designs are presented. Both are characterized in a very compact set-up and a flexible application area. The input and output beam diameter can be adapted easily to the parameters of an existing set-up. Furthermore, some valuable results of the characterization of both manufactured systems are shown.

Keywords: laser; beam shaping; gauss; top-hat; focused; aspheres

1. Introduction

The use of Gaussian laser beam profiles in industry and research is widespread, not least because of its flexibility. However, there are some applications for which the inhomogeneous beam profile and the considerable energy loss at the edge of the beam are not acceptable. While in measurement technology or biology a homogeneous intensity distribution is desired for optimal illumination, a top-hat beam profile in material processing can be used to improve the heat input into the material as well as optimize the process speed. It has already been shown in the past that refractive beam shaping concepts provide very good results (Dickey, 2014). Apart from their high efficiency and insensitivity to wavelength changes, the reason for this is their simple structure and consequently, their good manufacturability.

In the following, two compact aspheric beam shaping systems are presented, which are characterized by a particularly high flexibility. The input intensity distribution is a collimated Gaussian beam profile that is converted into a collimated and a focused top hat intensity distribution, respectively. Both systems enable a

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smooth integration into existing measurement setups. It is possible to use them with a collimated laser beam or a fiber-coupled source. Furthermore, the input and output beam size can be scaled, so that a wide range of top hat dimensions can be covered with only one beam shaping system. High optical performance can be achieved with both beam shaping systems. In this work, some selected design investigations as well as some valuable results of the practical testing are presented.

2. Optical Design of the Beam Shaping Systems

2.1. Afocal Beam Shaping System

The basic concept for beam shaping with aspheres was published by Frieden and Kreuzer (Frieden, 1965; Kreuzer, 1969). For this, the rays of a collimated Gaussian beam are redistributed by means of an asphere, so that a homogeneous intensity distribution is generated at a certain distance. At this position, a second asphere is positioned, which collimates the beam with the top-hat profile again and thus, generates a top-hat intensity distribution at a variable distance. The necessary re-distribution of rays as well as the calculation of the resulting shape of the aspheric surfaces is considered very often in literature (Dickey, 2014; Rhodes & Shealy, 1980).

The principle layout of the afocal beam shaping system, which is based on a patent of Kreuzer, is shown in Fig. 1a (Kreuzer, 1969). The incoming Gaussian beam having an input beam diameter of 10 mm @ 1 / e2 is redistributed so that the output beam has a uniform intensity distribution with a diameter of about 15 mm (FWHM). The system length in total is about 80 mm. Thus, the length could be reduced to half as compared to most systems available on the market. The reason for the long overall length is the fact, that the beam angles can be kept as small as possible having the large distances between the aspherical surfaces. Therefore, surface form deviations of the aspheric surfaces can be compensated. As a result of technological advances in aspheric manufacture it is now possible to produce aspheric surfaces much more precisely and so, this limitation no longer exists. The resulting simulated intensity distribution is shown in Fig. 1b for the optical design and for real surfaces (without mechanical tolerances).

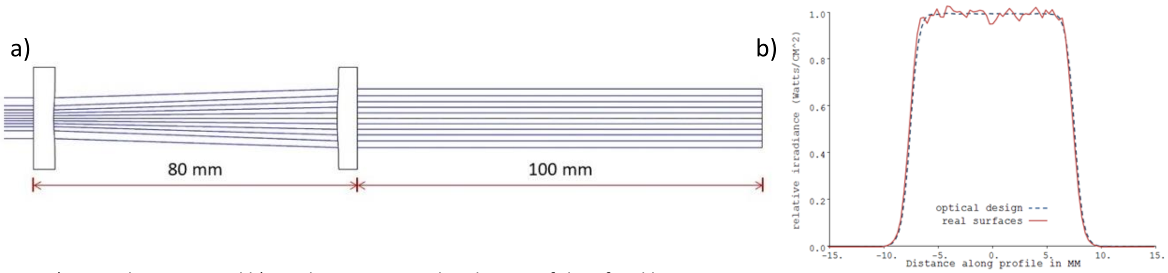

Fig. 1. a) Principle Layout and b) resulting intensity distribution of the afocal beam shaping system (for design case and real surfaces without mechanical tolerances)

2.2. Focused Beam Shaping System

While homogenous intensity distributions can be generated with the presented afocal beam shaping system in the range between 3 mm and 300 mm (FWHM), the main task of the focused beam shaping system is the generation of small top-hat profiles up to a maximum diameter of about 1 mm (FWHM).

However, this beam shaping system is based on a different beam shaping concept, which is described in more detail below.

The focused beam shaping system is derived from a known approach, based on diffraction theory and fourier transform correlation, was chosen (Goodman, 2005; Dickey, 2014). More precisely, it is assumed, that a simple lens performs a Fourier transform on the input intensity function and the corresponding Fourier counterpart occurs in its focal plane. That means, to generate a focused top-hat intensity distribution, which can be described by a circ-function, the resulting input intensity function must be a collimated Bessel-sinc shaped intensity profile. The theoretical background of this phenomenon is discussed several times in literature and need not be gone into here (Goodman, 2005; Dickey, 2014).

Since a collimated Gauss to focused top-hat intensity transformation was initially desired, a further beam shaping step from collimated Gaussian to collimated Bessel-sinc beam profile is necessary. This can be done with the help of a phase plate, as described in literature. The phase plate has a binary structure with an increased central part, derived of a known patent system (Cordingley, 1994). The principle layout of the beam shaping unit is shown in fig. 2.

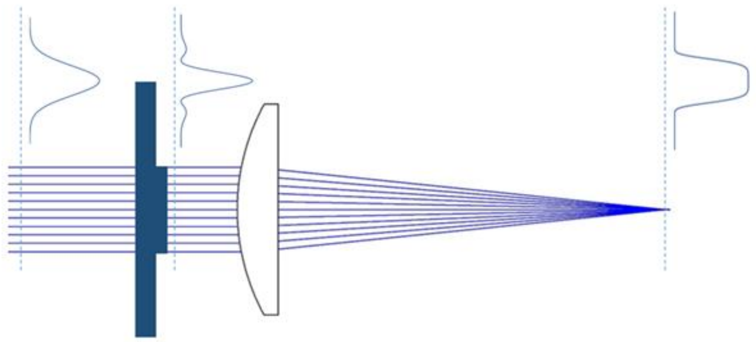

Fig. 2. Principle layout of the beam shaping system with all important intensity distributions (ray distributions in front and behind the phase plate are not displayed correctly due to ray tracing)

According to the working principle of the beam shaping system, it is possible, not just to generate one top-hat beam profile in the focal plane of a focusing lens, but create different beam profiles in different working distances. There is no need for additional components in the system set-up. In fig. 3 normalized beam profile sections along its propagation direction (z-axis) are summarized in one diagram. The detected range is ± 1.5 mm around the waist location. Further-more, the corresponding most interesting intensity profiles in the different working planes are shown, too.

With the help of this diagram the development of the several beam profiles can be demonstrated clearly. Basically, its propagation is symmetric to the beam waist. There are two wings, comprising planes with a smaller top-hat beam profile, a donut beam profile and a bigger top-hat beam profile. As one can see, the profiles on the right side with respect to the waist location appear more blurred than the beam profiles on the other side of the waist. These beam profiles have less defined edges and a considerable amount of energy in the sidelobes. This effect increases with the distance to the beam waist. For this reason, the second big top-hat profile is not considered here, since its slope and homogeneity is of insufficient quality for a top-hat beam profile.

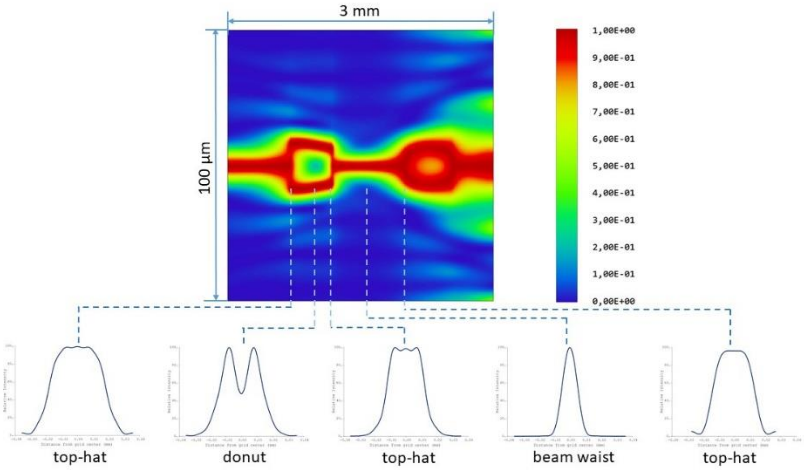

Fig. 3. Visualization of normalized beam profiles along the z-direction in a range of ±1.5 mm around the focal plane and corresponding beam profiles for the different planes

Another point, that can be seen from fig. 3 are the size and distance relations between the several intensity distributions. Having a closer look at the thickness of the profiles, shown in the plot, it is visible, that the bigger top-hat intensity distribution is twice as wide (FWHM) as the beam profile, which is located in the beam waist (@ $1/e^2$). Moreover, one can easily see, that the distance between the beam waist and the first (smaller) top-hat beam profile is approximately the same as the distance between the smaller top-hat and the bigger top-hat beam profile. The donut intensity distribution is located nearly in the middle of these two top-hat beam profiles. The distance relation between the profiles stays constant. However, the distances between the different profiles depend on the ratio of focal length of chosen focusing lens and input beam size (≙ numerical aperture) and the system wavelength.

3. Flexible Adaption of System Input and Output Beam Diameter

In practice, beam shaping is a complex process, especially if a beam shaping system should be added in an existing set-up. There are two aspects, which should be considered. The first is the adaption of the system input to the laser source and the second is the adaption of the system output to the individual set-up. It is essential to have a design, that can handle both tasks.

Due to the high flexibility of both beam shaping system it is possible not only to use it in combination with a collimated laser beam, but to use it with a fiber coupled source. For this, just some SPA™ Beam Expanders for the appropriate magnification and a SPA™ AspheriColl are needed. To scale the system output beam diameter one need to distinguish between both systems. For the afocal beam shaping system appropriate SPA™ Beam Expanders (as described for the input beam size) can be used to match the beam size (Fig. 4a). The scaling of the output beam diameter of the focused beam shaping system is also perfectly adaptable, since the size of the top-hat beam profile is scalable by the focal length of a focusing lens. So nearly arbitrary dimensions of top-hat beam profiles can be generated. An exemplary layout is shown in Fig. 4b.

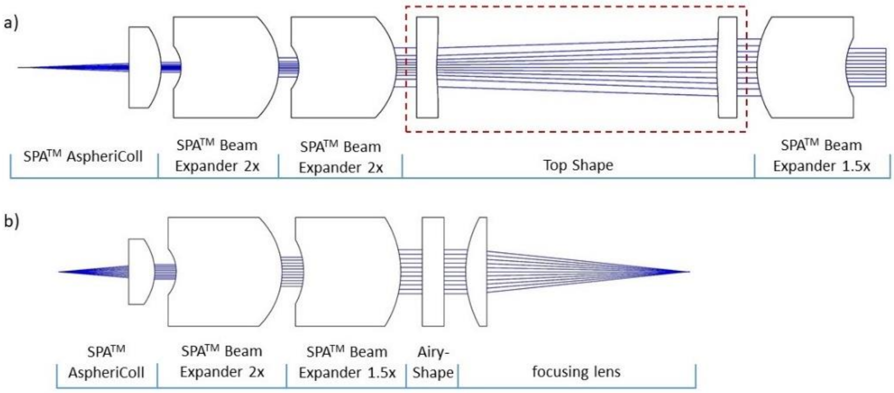

Fig. 4. Flexible adaption of input and output beam diameter a) for the afocal beam shaping system and b) for the focused beam shaping system

4. Experimental Results

Both introduced beam shaping systems were incorporated straight into a prototype and were tested practically. Some of the results are shown in the following. The set ups correspond to the ones, which are visualized in fig. 4a and b.

4.1. Afocal Beam Shaping System

A picture of the set-up is shown in fig. 5. As one can see the entire system length is about 190 mm, which is much more compact than comparable beam shaping units on the market.

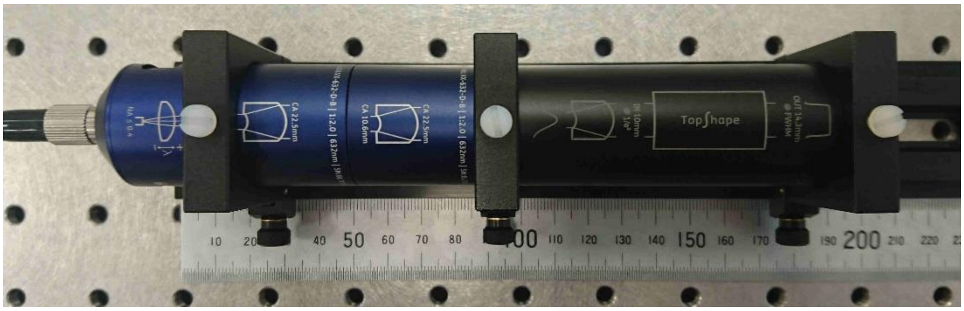

Fig. 5. Set-up for characterization, consisting of an SPA™ AspheriColl, several SPA™ beam expanders and the beam shaping system (black mount)

The generated beam profile, which is shown in fig. 6a, was measured with a beam profile camera (*Ophir SP928*) at the working distance of 100 mm with a coherent laser source (λ= 635 nm). The beam has passed 12 surfaces (including 6 aspheres). The resulting ISO Plateau Uniformity is 0.133 and the ISO Edge Steepness is 0.4. Additionally, a wavefront measurement was carried out with a *Phasics SID4-HR-307c* (300 x 400 pts;

λ= 635 nm) after passing 14 surfaces (including 7 aspheres). The resulting RMS wavefront error is 0.05 λ, which corresponds with a Strehl value of 0.9 (fig. 6b).

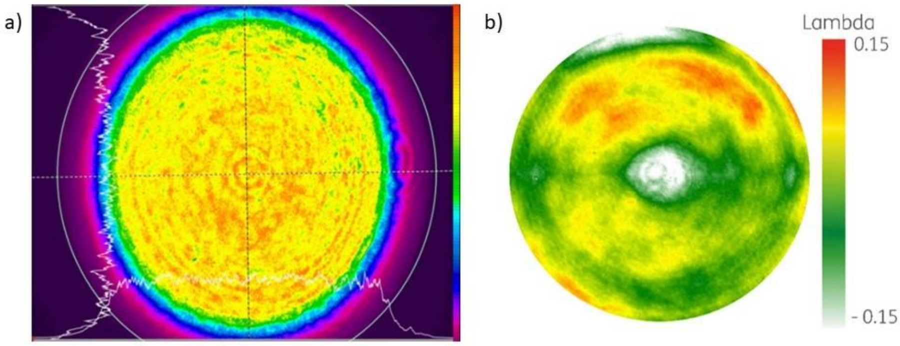

Fig. 6. a) Measured beam profile and b) measured wavefront of the afocal beam shaping system

4.2. Focused Beam Shaping System

Again, a picture of the second set-up is shown in the fig. 7. The system length in total is about 150 mm. With the help of a beam profile camera (*Ophir SP928*) the different characteristic beam profiles were investigated. Shifting the image plane the five intensity distributions were detected.

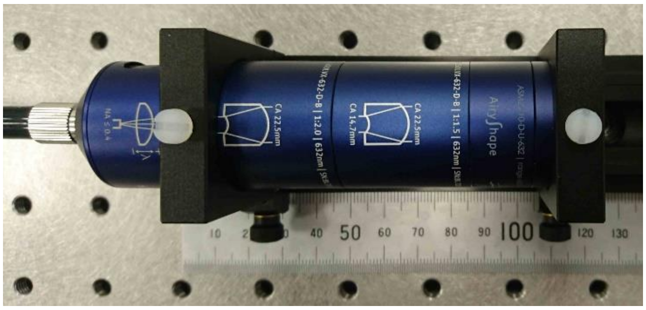

Fig. 7. Test set-up for characterization, consisting of SPATM AspheriColl, two SPATM Beam Expanders, the beam shaping system (black mount) and a focusing lens

In the fig. 8 the intensity distributions are shown in 2D and a cross-sectional plot. In addition, the z-position with respect to the beam waist and the corresponding beam profile diameter (FWHM, beam waist: @$1/e^2$) are shown, to give a rough orientation.

What can be seen from the fig. 8 is, that the function of the beam shaping system could be demonstrated successfully. The five interesting beam profiles are present. Furthermore, the distances between the several intensity distributions and their sizes are in good agreement to the results of the simulation (fig. 3). The beam profiles shown in fig. 8 are detected with a wavelength of 635 nm.

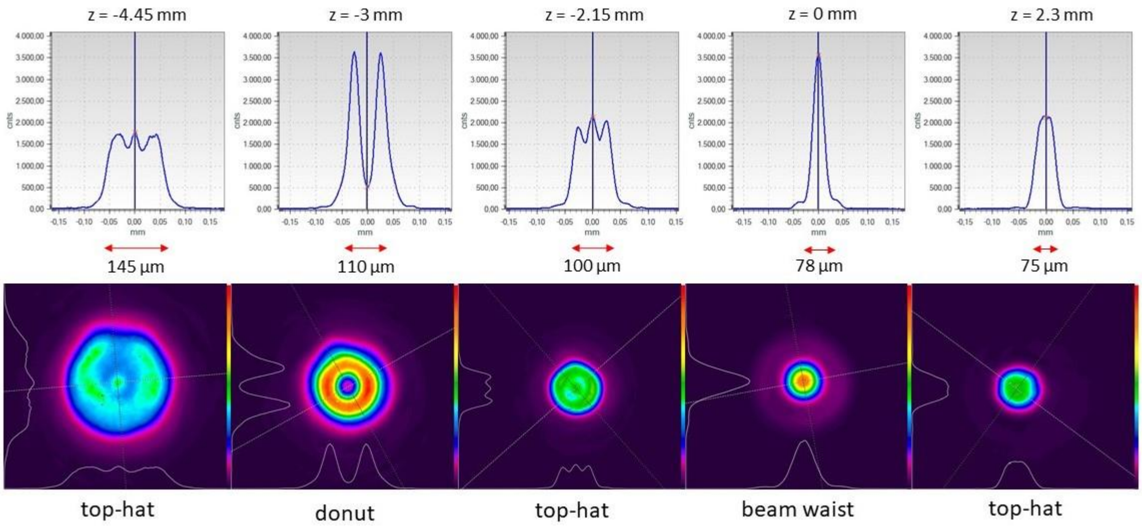

Fig. 8. 2D and cross-sectional plots of the characteristic beam profiles (taken by a beam profile camera) generated with a prototype of the beam shaping system (λ=635 nm)

5. Conclusion

In this work, two compact refractive beam shaping solutions were introduced. The first one is an afocal beam shaping system, which converts a collimated Gaussian beam into a collimated beam with a uniform intensity distribution. The second is a beam shaping system, generating a focused top-hat beam profile out of a collimated Gaussian beam.

The input and the output beam diameter is scalable, so that the systems are very flexible with respect to the field of application. They can be used not only with a collimated laser beam, but also with a fiber coupled source. Due to the modular approach and a special mounting concept the components just have to be screwed together and no additional alignment is necessary. This significantly simplifies the handling and the integration into existing set-ups, which could be proven by practically tests.

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