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Modular beam shaping and manipulation of polarization states using aspheric and freeform optical components

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- Invited Paper -

Abstract

The present paper presents three different methods for laser beam shaping depending on the individual application, which can be homogeneous illumination or certain intensity distribution at the focal plane of a laser beam. Additionally, a new concept for generating radial and azimuthal polarization using axicons is introduced. Besides an excellent optical performance, the main focus for all discussed systems is on compactness and the smooth integration into existing set-ups.

Keywords: *beam shaping; asphere; freeform; polarization; radial; azimutha; axicon*

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1. Introduction

In many laser applications a uniform intensity distribution, rather than the well-known gaussian intensity distribution is required to ensure maximum optical performance and process quality. So, beam shaping systems, which transform an incoming Gaussian beam into a so-called Top-Hat beam, are very important in this context. Since the shape and size of the desired Top-Hat intensity distribution varies, depending on the application, there will never be one single solution, which can handle all occurring beam shaping problems. Hence, in this paper three different beam shaping concepts will be introduced. All of them are designed in consideration of minimum required space and smooth integration into existing set-ups. The latter is ensured by the compatibility with asphericon's a|BeamExpander and a|AspheriColl for fiber coupled sources. The three different concepts are distinguished by their generated Top-Hat beam diameter, depending on, whether a homogeneous illumination (e.g. for microscopy) or a focused Top-Hat beam profile (e.g. for material processing) is needed, and their general shape (round or square shaped).

Besides the shape and the size of the uniform intensity distribution, also the polarization state of the working laser beam is a considerable factor, that influences the performance and process quality, especially, in the field of laser material processing. As an example, it is well-known, that a linear polarized beam is not advantageous for laser cutting, where the machining direction is changing frequently. The reason is the material absorption, which depends on the cutting direction, resulting in flash at the edges of the material. These effects can be avoided when the polarization state of the laser beam is changed to radial or azimuthal. The material absorption will not have a preferred direction and consequently, a cutting direction independent removal of material can be ensured. Additionally, the focusablility of the laser beam can be improved using radial polarized laser beams. Therefore, the second part of this paper deals with the introduction of a new concept to transform linear or circular polarization of a laser beam into radial or azimuthal polarization using axicons.

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2. Gauss to Top-Hat Beam Shaping using aspheres and freeforms

1.1 Generation of round shaped collimated Top-Hat illumination

There are several laser applications, e.g. in the field of microscopy, which aim for a uniform illumination of the sample plane, since the achievable resolution of the measurement method is directly connected with the illumination conditions. Usually, the illuminated region needs to be in mm range (> 5 mm) and the working distance differs from one application to another. Simultaneously, the intensity variation within the illuminated region should not exceed a certain level to guarantee optimum resolution.

A suitable solution would be to transform the collimated Gaussian beam, which is coming out of the laser source, into a collimated homogeneous intensity distribution nearly without energy loss. The basic concept for such a beam shaping was published by Frieden (1956) and Kreuzer (1969). The optical system consists of two aspheres positioned in a certain distance to each other. The first asphere re-distributes the rays of the incoming Gaussian beam and the task of the second asphere is the re-collimation of the so-called Top-Hat beam.

Beam shaping by its nature is a very complex process, which is very sensitive to deviations from its original design conditions. It works best when used with the same entrance beam profile as used in the optical design. Since this ideal situation basically never occurs, a stable solution is necessary, which can handle changes in input beam diameter and provides a flexible adaption to the parameters of individual set-up. An exemplary setup containing the afocal beam shaping system is shown in Fig. 1. It is designed for an incoming Gaussian beam diameter of 10 mm @ $1/e^2$. In combination with the a|AspheriColl and the a|BeamExpanders it can be employed either with a collimated laser beam or a fiber coupled source to adapt the parameters directly from the source to the beam shaping system (Moehl, Fuchs, 2016; Fuchs, Wickenhagen, 2015). The overall length of the entire set-up, shown in Fig. 1, is about 250 mm. Additionally, the output beam diameter can be scaled using further a|BeamExpanders. Thus, Top-Hat beam profiles in a range from 3 mm to 22 mm in diameter can be generated with the same beam shaping system.

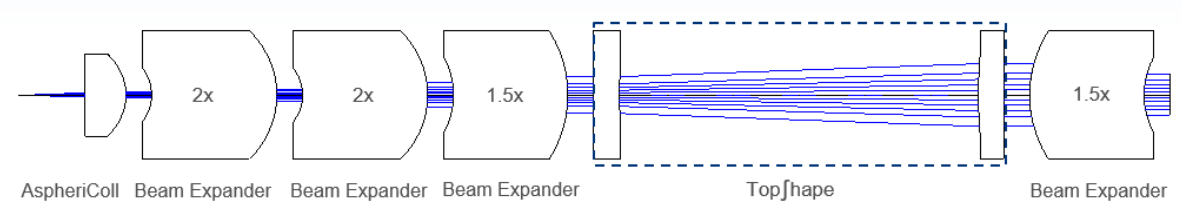

Fig. 1: Flexible adaption of input and output beam diameter of the afocal beam shaping system (a|TopShape)

Furthermore, the beam shaping system was characterized with respect to the resulting intensity distribution and wavefront quality. For this, the set-up, shown in Fig. 1 (without the last a|BeamExpander), 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 (Fig. 2a). Additionally, a wavefront measurement was carried out for the set-up, shown in Fig. 1, 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. 2b).

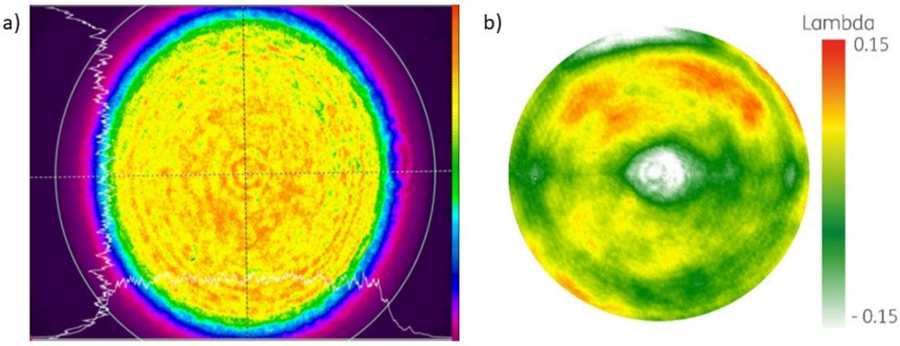

Fig. 2a and b: a) Measured beam profile and b) measured wavefront of the afocal beam shaping set-up

1.2 Generation of square shaped Top-Hat intensity distributions

Top-Hat beam profiles can improve the efficiency of laser application in many cases. But sometimes a square shaped Top-Hat, rather than a round shaped distribution would be much more advantageous. In opposite to round shaped Top-Hat intensity distributions, which can be generated with the help of rotational symmetric lenses, the square shaped Top-Hat- beam profiles are only possible with the help of freeform elements. One approach is to enhance the well-known Alvarez lenses to achieve a square shaped homogeneous intensity distribution.

The basic principle of the so-called Alvarez lenses was introduced in 1970 and consists originally of two elements with complimentary two-dimensional cubic surfaces separated by a small gap. These cubic surfaces are translated laterally with respect to one another (Alvarez, Humphrey, 1970; Babington, 2015). In Fig. 3 the working principle of an Alvarez lens is shown. When both elements are placed with their vertexes on the optical axis, the induced phase variations cancel out. By lateral displacement of the freeform elements against each other a positive and a negative optical power, respectively, can be achieved.

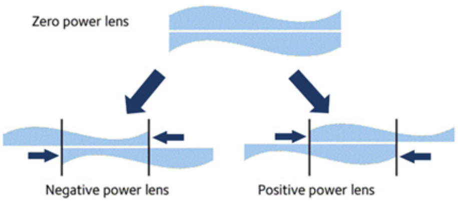

Fig. 3: Working principle of an Alvarez lens

However, this concept is limited in terms of achievable wavefront quality. Due to the latest progress in freeform manufacturing technology nearly arbitrary surface shapes can be generated. Subsequently, the original approach can be enhanced to enable a diffraction limited wavefront quality. For this, the original surface form description needs to be extended, for example by some Zernike terms, so that the general surface form can now be described as

$$z(x,y) = axy^3 \frac{a}{3}x^3 + bx + \sum_{i=1} Z_i(x,y) \tag{1}$$

whereas a and b are fixed constants and Z_i represents the Zernike terms.

Depending on the surface shape and preferred displacement direction, different optical effects can be generated. One of these effects is the generation of square shaped Top-Hat intensity distributions in varied sizes and working distances out of an incoming Gaussian beam by axial displacement of the lens elements. The principle layout of the beam shaping system is shown in Fig. 4a and the corresponding illumination at the image plane is visualized in Fig. 4b.

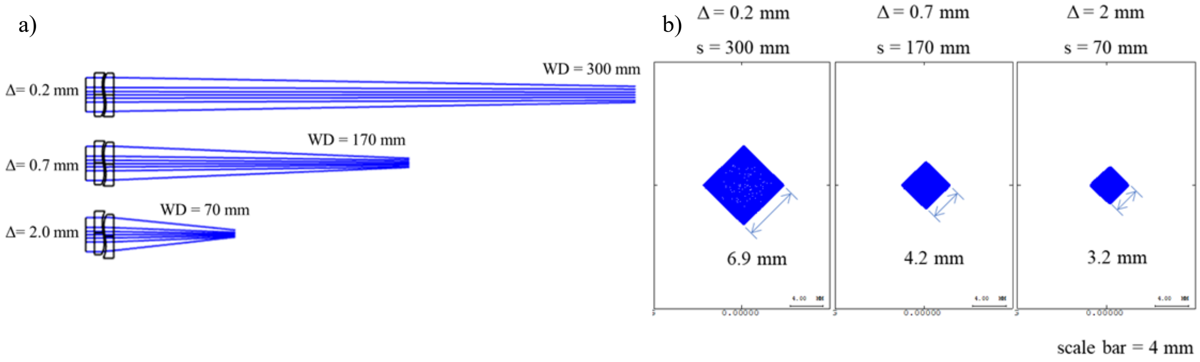

Fig. 4a and b: a) Layout of the freeform beam shaping system with exemplary configurations and b) the corresponding illumination at the image plane

1.3 Generation of focused Top-Hat intensity distributions

Especially, in the field of laser material processing certain intensity distributions, e.g. Top-Hat or donut profiles, in the focal plane of an optical system are demanded to achieve different machining tasks. Usually, the required spot sizes reach values in the µm range (< 500 µm). To ensure the diverse beam profiles in the focal plane a different approach is taken. This approach is based on diffraction theory and Fourier transform correlation and is introduced briefly in the following (Goodman, 2005; Dickey, 2014).

The beam shaping system consists of two components. The first element is a phase plate comprising a binary structure. This phase plate is used to achieve a collimated Bessel-sinc shaped intensity profile and was derived in a known patent system (Cordingley, 1994). The second element is a focusing optics, which can be a single lens or for example an F-θ lens. The lens basically performs a Fourier transform of the input intensity distribution and the corresponding Fourier counterpart occurs in its focal plane, which is a Top-Hat intensity distribution in this special case. Combining the phase plate and the focusing optics to a beam shaping system that performs a Gauss to Top-Hat transformation, as shown in Fig. 5. As already indicated in section 1.1, a modular approach was also chosen here to enable smooth integration of the beam shaping system into existing set-ups. Consequently, the beam shaping set-up can be used with a collimated laser beam as well as a fiber-coupled source. For this, only some suitable a|BeamExpanders and the a|AspheriColl need to be added to the beam shaping system. Additionally, the size of the resulting Top-Hat intensity distribution can be scaled by the focal length of the focusing optics (e.g. F-θ lens). One possible set-up is shown in Fig. 6.

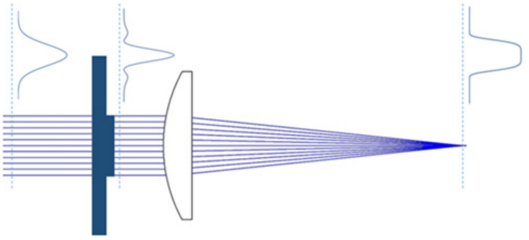

Fig. 5: Principle layout of the focused beam shaping system with important intensity distributions (ray distributions in front and behind the phase plate are not displayed correctly due to ray tracing)

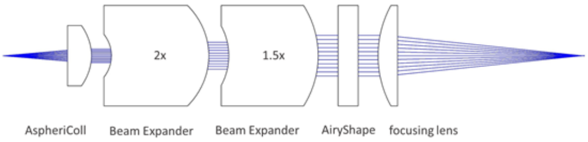

Fig. 6: Flexible adaption of input and output beam diameter of the focused beam shaping system (AiryShape)

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. 7 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. Furthermore, the corresponding most interesting intensity profiles in the different working planes are shown, too.

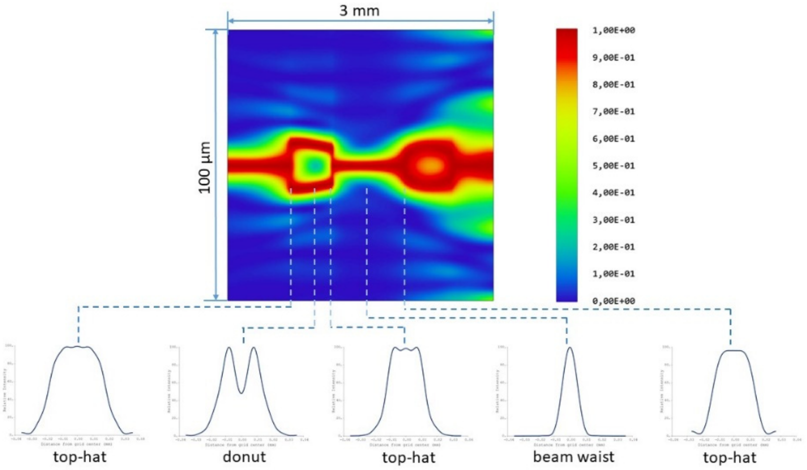

Fig. 7: Visualization of normalized beam profiles along the z-direction in a range of ±1.5 mm around the focal plane and corresponding beam profiles for the different planes

The beam shaping setup, shown in Fig. 6, was investigated with respect of the resulting characteristic beam profiles with the help of a beam profile camera (*Ophir SP928*). Shifting the image plane the five intensity distributions were detected. 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/e2) are shown, to give a rough orientation. The beam profiles shown in Fig. 8 are generated with a wavelength of 635 nm.

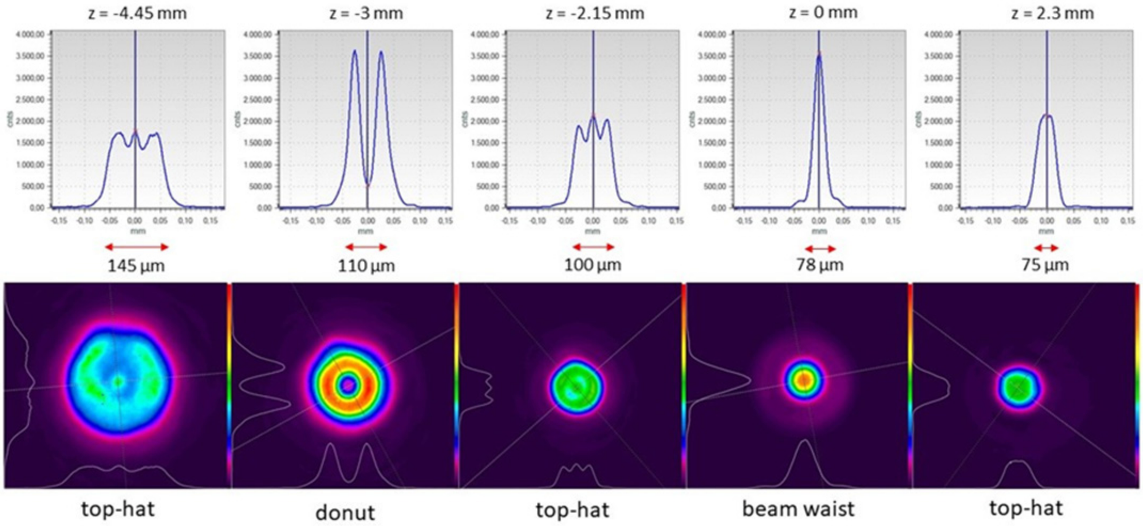

Fig. 8: 2D and cross-sectional plots of the characteristic beam profiles (taken by a beam profile camera) generated with a prototype of the beam shaping system (λ=635 nm)

3. Generation of radial and azimuthal polarized light using axicons

Another approach to improve the beam quality and process efficiency is to manipulate the polarization state of the working laser beam. Using a radial or azimuthal polarized laser beam for laser material processing results in uniform material removal independent from cutting direction as well as improved focusability (Golyshev et al., 2015; Phelan et al. 2011). By default, laser provide linear or circular polarized light. So, what is needed, is a compact concept to transform linear or circular polarization of a laser beam into radial or azimuthal polarization.

A basic concept of generating radial and azimuthal polarized light using monolithic axicons and two additional halfwave retarders was demonstrated before (Zhang, Qiu, 2013). The polarization transformation was realized by total internal reflection. Unfortunately, that approach had the disadvantage of having large dead-zones in the center due to manufacturing via DT. In our new approach reflective axicons are used to achieve the demanded manipulation of phase. The principle layout of the polarization transformer consisting of a pair of inner convex and outer concave axicons, mounted on a plane parallel plate, is shown in Fig. 9.

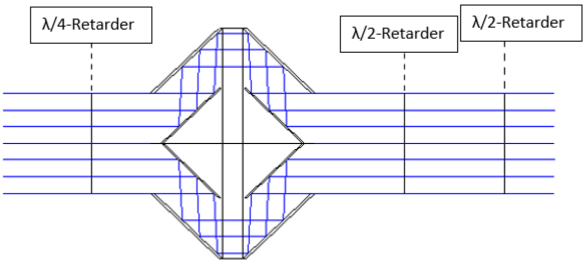

Fig. 9: Layout of the polarization transformer

Linear polarized light is transformed to circular polarized light by a quarter-wave retarder. Four reflections at high reflective conical surfaces generate a total phase retardation of π/2. With the use of two halfwave retarders positioned behind the axicon, all locally linear polarizations states are re-positioned in radial or azimuthal way, as visualized in Fig. 10.

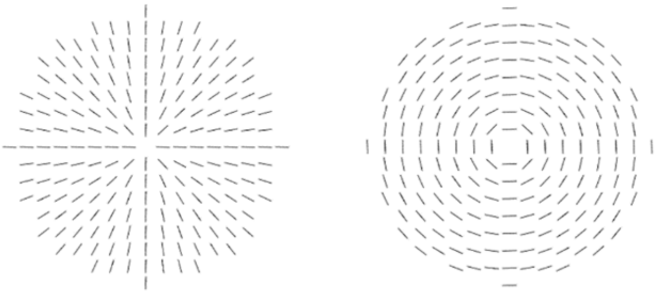

Fig. 10: Visualisation of the resulting radial polarization (left) and azimuthal polarization (right), respectively

The polarization transformer is designed to be compatible with the different a|BeamExpanders in terms of wavelength range and input and output beam diameters. In a set-up in combination with a|BeamExpanders transmission intensities of about 80% can be already achieved. Furthermore, it is possible to use the polarization transformer in combination with a fiber-coupled laser source (using the a|AspheriColl). The next step of improvement will be a significant increase of the transmission intensities to a level of above 98% by employing optimized dielectric HR-coatings.

4. Conclusion

The efficiency of a laser process or a specific application can be improved in many ways. Depending on the individual task either the intensity distribution as well as the shape of the beam or the polarization state can be the crucial parameter, which helps to increase the quality and the performance of the laser process, respectively. In this paper three different methods for converting the Gaussian input beam into a Top-Hat intensity distribution are introduced. Furthermore, a new compact approach for manipulating the polarization state of a laser beam using axicons is presented.

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