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Beam shaping with free-form optics for optimal material processing

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Abstract

The number of applications in material processing, where the focal intensity distributions should deviate from the Gaussian shape, is rapidly increasing. Of particular interest are not only top-hat or donut distributions, but also non-rotationally symmetric distributions such as squares or ellipses. We present refractive freeform beam shaping elements to generate such focal distributions. Moreover, these elements provide patterns in the focal region with 3x3 or 4x4 spots. Here, the absolute size of all focal distributions is scalable with the NA of the used focusing lens.

Simulation results will be compared with measured intensity profiles to show good agreement. Furthermore, first experiments on stainless steel will show the different effect of the various intensity distributions on the material interaction. Since the refractive beam shaping elements used are also low dispersion, this opens new possibilities for material processing with ultrashort laser pulses.

Keywords: beam shaping; laser material processing; surface functionalization; ablation

1. Introduction

Intensity distributions which deviate from a Gaussian profile in the focal plane are finding more and more applications. Many experiments and industrial applications require intensity distributions which are nominally constant over a certain beam cross section, e.g., in the field of laser material processing, laser-matter interaction and lithography. With a constant intensity distribution, the largest possible area can be irradiated with the optimum power density for the process without too much energy going unused in the flanks. Such

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top-hat intensity distributions have already been used to increase the homogeneity of laser-induced periodic surface structures (LIPSS) [1] or to halve the processing time [2]. Another optimization option is to shape the usually rotationally symmetric top-hat distribution into a square spot in order to process large areas without gaps and with little overlap.

2. Operating Principle of beam shaping in the Focal Plane

The beam shaping in focus presented in this paper is performed by two elements. On the one hand a conventional focusing optics is used, on the other hand a beam shaping element. The advantage of this approach is that the beam shaping element is independent of the focusing optics and thus compatible with all focal lengths and can be easily integrated into existing setups.

Beam shaping at the focus follows the principle of Fourier optics: the field strength distribution at the focus of a lens corresponds to the Fourier transform of the field strength distribution of the collimated input beam. For the rotationally symmetric case the Fourier transform of a top-hat function is the sinc function (equivalent to the first kind zero order Bessel function). Consequently, the actual task is to convert a Gaussian distribution into a sinc field distribution (or sinc^2 intensity distribution). In the approach we have chosen, the conversion is done in the collimated beam.

Since the sinc^2 distribution has an infinite number of zeros, in practice only an approximation of this distribution is possible. We therefore restrict ourselves to approximating the sinc^2 distribution up to and including the first secondary maximum, which already achieves a top-hat distribution in the focus. However, for optimal slope, additional higher order sidelobes would have to be considered. The generation of an approximated sinc^2 distribution is done about a binary phase plate [3], which is schematically shown in Figure 1. The centrally incorporated step generates a phase offset of circa π. The diameter of the central step corresponds to the 1/e2 diameter of the Gaussian input beam.

Due to the phase manipulation, the intensity distribution changes in the entire focal region. Thus, in addition to top-hat profiles, a characteristic donut profile and a Gaussian-like beam waist are also formed. These profiles arise in different planes relative to the focus and can be achieved by shifting the image plane. The diameter of all these profiles is determined solely about the NA of the focusing lens. This means that the desired size of the top-hat or donut can be changed both about the focal length of the focusing optics and about the beam diameter. In addition, this scaling allows a considerable shortening of the working distance in case of subsequent beam reduction, so that construction length can be saved.

For the generation of a square top-hat distribution in the focal plane the approach stays the same, but the phase plate becomes a freeform surface.

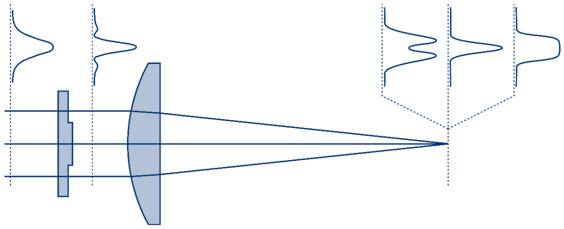

Fig. 1. Basic setup for rotationally symmetric beam shaping in the focus. The Gaussian input beam is transformed into an approximated sinc^2 distribution by a binary phase plate. Focusing produces top-hat and donut profiles near the beam waist.

3. Squared Intensity Distributions in the Focal Plane

The results of [2] showed that the rotationally symmetric phase plate (a|AiryShape) can be combined very well with F-Theta optics, which is essential for large-scale and high speed surface processing. The scanning motion performed in this process gives a clear x-y symmetry. Thus, it is obvious to transfer this symmetry to the focal intensity distribution as well and to form a square focus. This allows to minimize the overlap of individual processing areas and to homogenize the energy deposition. To be able to integrate the beam shaping of the square focus into existing setups without any problems, a basic requirement for the optics design of such a beam shaper is, that the focusing optics remain rotationally symmetrical. Consequently, only a freeform beam shaping element can achieve the required symmetry breaking.

The further developed beam shaping element for square focus distributions is based on the same principle as that of the rotationally symmetrical a|AiryShape. This means, that these refractive beam shaping elements are also low-dispersion and, thus, suitable for applications with ultrashort pulsed lasers (fs-laser). Furthermore, they are suitable for applications with high laser powers and, in contrast to DOEs, are easy to clean. In addition, it is also true here that the absolute size of the distribution is determined by the NA of the focusing optics and is, thus, scalable.

Figure 2 shows both simulation and measurement results of the free-form beam shaping element for the square focus (wavelength λ = 1064 nm, focal length f = 200 mm). Equivalent to the rotationally symmetric a|AiryShape, a donut distribution is formed in front of the focus, which is enclosed by two top-hat profiles. Behind the beam waist, another top-hat profile forms. We find an outstanding agreement between the simulation and measurement results, especially with respect to intensity distribution, diameter, and absolute position of the image plane. The slight tilt and associated asymmetry of the top-hat profiles is due to the current holder concept and is currently being revised.

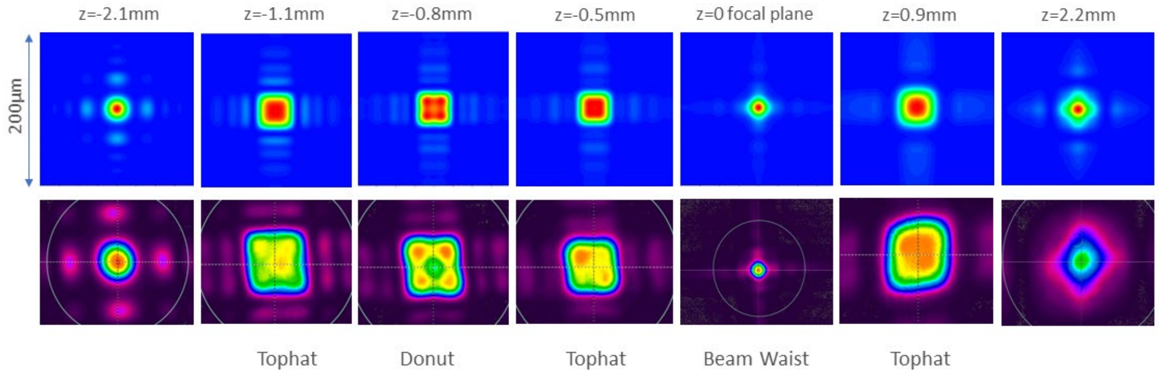

Fig. 2. (top) Simulation and (bottom) measurement of the squared intensity distribution in the area of the focal plane (λ = 1064 nm, f = 200mm). The shift of the image plane is indicated by the z-position relative to the focus of the lens.

4. Structured x-y Intensity Distributions

Depending on the application, not only larger diameters but also periodically modulated x-y intensity distribution may be of interest. This can also be achieved with a free-form optical beam shaping element. Figure 3 shows the intensity distributions at several millimeters in front of the focal plane. Both two- and threecount donut distributions are obtained, which are larger than the near-focus spots by a factor of 1.5 to 4. At this point, it should be emphasized that the relevant intensity distributions arise in front of the actual focus of the lens. Thus, the beam waist with potentially high-power densities, which would usually interfere with beam shaping, does not pose a problem.

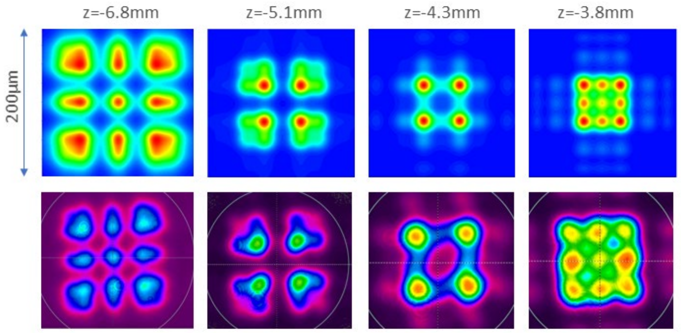

Fig. 3. (top) simulation and (bottom) measurements of the squared intensity distributions in planes well in front of the focal plane.

Single spot experiments on stainless steel with ultrashort laser pulses (300 fs) will show how these square intensity distributions modify the surface structure. In particular, those profiles that exhibit reduced intensity in the center will be of particular interest for further studies on micro-marking and surface functionalization. In addition, we will investigate whether the processing time can be further reduced by square focus distributions.

5. Surface Structuring with Squared Intensity Distributions

The adequate function of the beam shaping element was proven by single spot experiments with linearly polarized fs-laser pulses (wavelength $\lambda = 1025$ nm, pulse duration $\tau = 300$ fs, repetition frequency $f_{rep} = 100$ kHz) emitted by a diode pumped Yb:KYW thin disc fs-laser system (JenLas D2.fs, Jenoptik, Germany). As described in [2], the fs-laser beam was focused by a galvanometer scanner (IntelliScan14, Scanlab, Germany) equipped with a f-Theta objective (JENar, Jenoptik, Germany) with $f_L = 100$ mm. Figure 4 compares the calculated intensity profiles with scanning electron micrographs obtained from the surface of commercially available austenitic stainless steel (X2CrNiMo17-12-2, Outokumpu, Germany) irradiated with $N = 20$ pulses with a single pulse energy $E_{imp} = 13$ µJ at normal incidence and under ambient air. For this purpose, the substrate material was polished prior to laser processing with a preparation procedure to a mirror finish with an average surface roughness of about 4 nm. The micrographs demonstrate that by choosing the appropriate z-position, i.e. the distance of the substrate surface relative to the focusing unit, the calculated intensity distributions allow for a well-defined ablation of the material surface. Moreover, LIPSS typical for the utilized parameters can be observed on the stainless steel surface [2]. The comparison of the Gaussian beam waist ($z = 0$ focal plane) with the Tophat position ($z = -0.5$ mm) illustrates that the novel beam shaping element provides defined squared intensity distributions in the focal plane for tailored surface patterning on the micro- and nanoscale. This promises to improve homogeneity and processing time, especially for large-area patterning by unidirectional scanning of the fs-laser beam over the sample surface, which is the subject of current investigations.

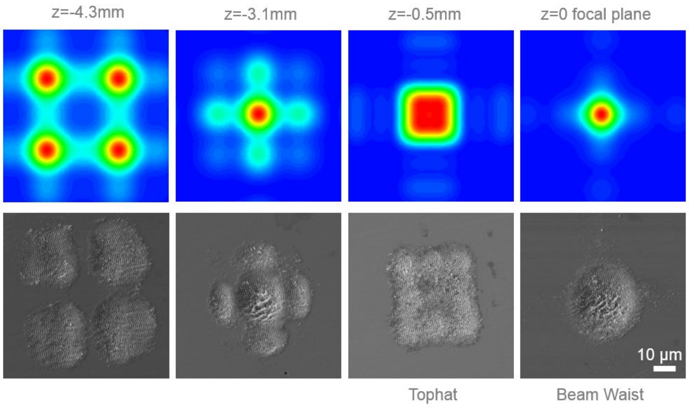

Fig. 4. (top) simulation of the squared intensity distributions and (bottom) scanning electron micrographs of stainless steel surfaces after fs-laser irradiation with N = 20 pulses and a single pulse energy E_{imp} = 13 µJ.

6. Summary

In this paper, a new method for converting a Gaussian input beam into a focal quadratic intensity distribution has been presented. In addition to square top-hat distributions, square donut distributions and other complex square structures can be generated about the presented principle, which are promising for various applications in laser materials processing. The NA of the focusing optics determines the edge length of the top-hat, so that the spot size can be individually adjusted according to the application. Furthermore, the mode of operation of the compact beam shaper allows an uncomplicated integration into existing set-ups. From experiments with the rotationally symmetrical predecessor version, it is known that this type of beam shaping can be combined with F-theta optics without restriction, so that scanning processing methods in particular benefit from the x-y symmetry of the focus. Single spot experiments demonstrate a very good agreement between beam shaping simulation and the resulting ablation spot geometry, which is an important basis in particular for large-area surface nanostructuring.

References

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