Design of freeform optics for the realization of application adapted intensity distributions with small extents

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When the target intensity distributions for non-imaging freeform optics become very small, the thickness and curvature of the designed optics increase resulting in numerical instabilities during the design or in manufacturing challenges. Thus, we present a design method to combine a comparatively flat freeform optic with a high NA objective standard lens to create small (< 500 µm) intensity distributions.

1 Introduction

In laser material processing applications such as laser structuring or marking, small geometric shapes are generated on the surface of a workpiece. Conventionally, these patterns are generated by moving a focused single-mode laser beam with a scanner over the surface. However, with regards to processing speed and efficiency, it is advantageous if the pattern can be generated with a single light exposure with a laser beam's intensity distribution that shows the respective geometric shape.

A means for generating such intensity distributions are non-imaging freeform optics whose surfaces are shaped in such a way that incoming light is deflected locally in a defined direction so that in total an intensity distribution forms on the workpiece surface. However, the geometric patterns in the mentioned laser applications are comparatively small (< 500 µm) requiring optics with high NA. As a result, the designed freeform optics are rather thick which leads to instabilities in the design software as well as to manufacturing challenges. Therefore, in this work, an approach is presented where a rather flat freeform surface is combined with a secondary, conventional high NA objective lens.

In Section 2, the design method is summarized and in Section 3, some design examples are shown and discussed.

2 Design Method

The design method is based on previous works [1] on freeform optics design. In these numerical approaches, the freeform optics is designed in a three-step process. First, a mapping between the source and the target intensity distribution is computed based on the solution of a Monge-Ampere equation. In this calculation, no optical surface is introduced yet. The mapping then prescribes where each part of the source irradiation must be transported by the freeform optics. Based on this result, a first guess for the freeform surface is derived in the second step. Here, the surface is triangulated, for each triangle a ray is generated, and the mapping is interpolated to obtain the target position for this ray. The surface is then found by a least-square minimization of the current and the computed target position where the current target position is obtained through propagation. The design is adapted in the third step by optimizing the flux in each projected triangle on the target.

The inclusion of a secondary optic into this algorithm is straightforward. The first step stays the same as no optics is considered yet. In the second and third step, the propagation between the freeform surface and the target plane is extended so that the free-space propagation is replaced by a ray tracing through the secondary optics. As only the target position and flux respectively are compared, this has no further influence on the optimization strategy.

3 Results and Discussion

For a first demonstration, a laser beam with Gaussian intensity distribution with a radius of 2 mm and a wavelength of 660 nm is reshaped first by a one-sided N-BK7 freeform lens and then by an ideal objective with 10 mm focal length and NA = 0.37. The target distribution consists of several geometric shapes, as shown in Figure 1.

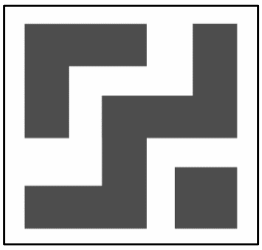

Figure 1: The target intensity distribution consists of several geometrically shaped blocks. The distribution's size is 200 µm x 200 µm

The resulting height profile of the freeform surface and the obtained intensity distribution are shown in

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Figures 2 and 3 respectively. It is important to mention that here and in the following all intensity distributions have been computed in wave-optical simulations. As a result, the freeform surface shows small height variations (≤ 70 µm) and the target extent is small with only minor diffraction artefacts.

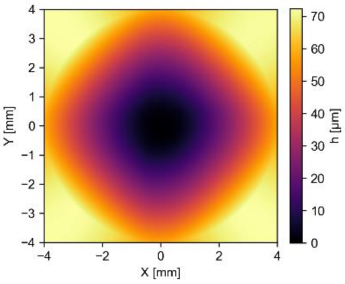

Figure 2: Height profile for the designed freeform optics. The maximum height difference is approximately 70 µm.

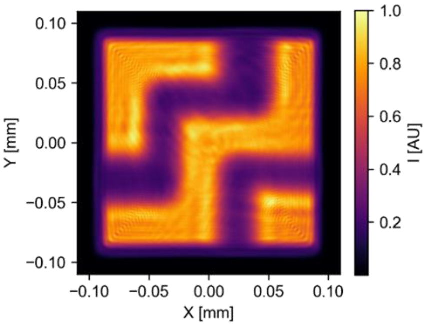

Figure 3: Intensity distribution obtained with the freeform optics from Figure 2.

In a further analysis, the focal length of the secondary ideal objective in this setup has been varied and the intensity distribution has been computed. While the relative distribution stays identical, the absolute size adapts linearly. Consequently, the freeform optics can be interpreted as a phase mask that shapes the far-field pattern.

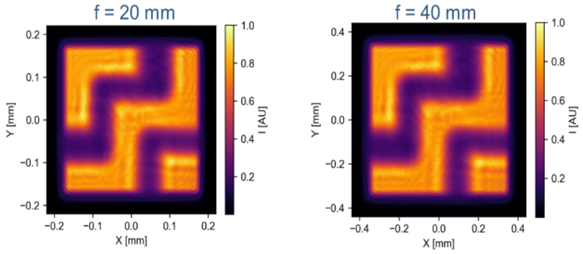

Figure 4: Intensity distributions obtained with two different objective lenses with focal lengths of 20 mm and 40 mm respectively.

This relation can be utilized to derive phase masks from the freeform optics which for example can be applied in diffractive optical elements (DOEs) or spatial light modulators (SLMs). Assuming collimated light and normal incidence, the freeform optic's height profile H can be transformed into a phase by the relation:

$$\Phi = \left(H \cdot \frac{2\pi}{\lambda} \cdot (n-1) \right) mod\ 2\pi$$

with wavelength λ and index of refraction n. For the example from Figure 2, the phase mask generates an intensity distribution equivalent to the one of Figure 3 (data not shown).

With decreasing target – and feature – size, diffraction effects increase. Figure 4 shows simulation results for freeform optics generating distributions with 0.1 mm and 0.05 mm edge lengths. Although the general shape is still recognizable, diffraction causes irregularities especially at the distribution's edges. Therefore, for very small extents, it is necessary to account for wave-optical effects.

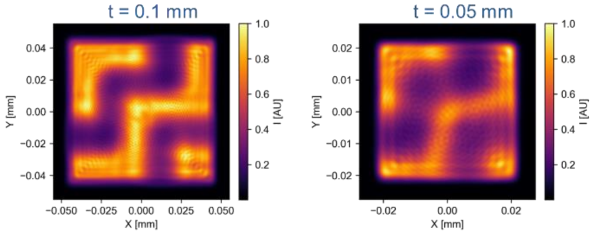

Figure 5: Intensity distributions of freeform optics for varying target sizes.

4 Summary & Conclusion

In this work, an approach for the design of optical systems that generate flexible intensity distributions has been developed by combining a freeform optics with a conventional objective lens. Moreover, by varying the objective lens' focal length, the intensity extent can be adapted which is a result of the correspondence of the freeform optics with a phase mask.

However, for a further miniaturization of the intensity distribution, wave-optical effects must be considered in the design process. Here, further work is required.

5 Acknowledgements

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