Micro-optical Free-Forms: Design and Fabrication

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Abstract: Free-form optical elements can be advantageously used to tailor diffractive optical functions, e.g. their chromatic behaviour. Their realization requires dedicated high-precision lithographic fabrication technologies.

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1. Introduction

The use of non-spherical surface shapes on the micro-scale for the realization of optical functions is state of the art since the advent of diffractive optics. The reason for this essential difference to conventional macro-optical elements is based on the different fabrication technologies used for their realization. For macroscopic elements like lenses, historically grinding and polishing techniques are used which were only recently extended by computer controlled local shaping options or ultra-precision machining techniques for achieving free-form surfaces with sufficient precision. On the microscopic scale the realization of micro-optical elements was always related to lithographic techniques which are intrinsically not restricted to spherical surface shapes but do have other limitations like being restricted to limited profile depths.
From a design point of view, it's a trivial conclusion that the use of surfaces shapes not restricted to spheres gives larger freedom and advantages for achieving a design target. On a micro scale such optical functions can be realized easily by diffractive structures (or meta-surfaces as they are also called recently, but that's essentially the same with respect to optical functionality).
However, to fully exploit the potential of micro-optical free-forms new design approaches are required which significantly go beyond the standard diffractive element design techniques like the Iterative-Fourier-Transform-Algorithms. In addition, an extension of the conventional fabrication techniques, especially towards the highly precise realization of deeper surface profiles, is necessary.

2. Design considerations for micro-optical free-forms

Micro-optical free-form surfaces are not dedicated to replace conventional optics but they can add additional functionalities not achievable with any other kind of element. While conventional diffractive optical elements (DOE) are widely used for similar extensions, they typically show a specific chromatic behaviour. Sometimes these effects are part of the desired optical function, e.g. for the hybrid diffractive-refractive achromat, in other applications they strongly restrict the usability of the DOE.
For the design of DOEs typically projection algorithms like the well-known Iterative-Fourier-Transform-Algorithm (IFTA) are applied. They compute a wave-front of a monochromatic wave transmitted through a DOE wrapped to a phase range of [-π, π]. By using the so-called thin element approximation (TEA) this wave-front or phase function is then directly transferred into a surface profile of the DOE. Illuminating such an element by wavelengths differing from the design wavelength results in the occurrence of typically undesired diffraction orders. In imaging applications this leads to scatter losses, spurious ghost images, or chromatic aberrations.
Maintaining the freedom connected with the arbitrary surface shapes and getting rid of these chromatic effects at once, requires modifications in the geometry of the element surface and thus, the design algorithms. In particular, the elements must not exhibit the typical 2π phase jumps which are pinning the surface to a specific design wavelength. However, for achieving an achromatic behaviour this condition alone is not sufficient. It is necessary to extend the depth of the element towards higher multiples of the wavelength, forcing the element to operate in higher diffraction orders. Consequently, the interaction of the light will shift from pure diffraction towards an intermediate regime between diffraction and refraction. Then a change of the illumination wavelength will still shift the light between adjacent diffraction orders but their propagation characteristics differ only marginally. As a result, this leads to an almost wavelength independent behaviour. To design such elements an extension of the IFTA with refractive techniques is necessary.

3. Gray-scale lithography for micro free-forms

For the realization of elements designed according to the principles described in the previous section a dedicated fabrication process is needed as their profile depth is considerably larger than that of a conventional DOE. A suitable technology is gray-scale photo-lithography. Specially developed tools are available which can sequentially expose thick photo-resist layers with locally varying doses which can be transferred into an exposure dose dependent profile depth during the wet-chemical development process. It needs to be noted that the required accuracy of the profile fabrication is still in the range of λ/4 … λ/10, which is difficult to achieve for profile depths of 10µm or more in such an analogue process. In particular, this requires a large amount of dose levels (>250) to be accurately addressed during the writing process. Furthermore, the strongly non-linear resist response needs to be calibrated precisely.
We have developed a dedicated tool for such a gray-level exposure operating with a UV-LED illuminated LCoS-

imager for the generation of the exposure dose distribution. This micro-display is then imaged onto the photoresist coated substrate by a specially developed projection optics. The system is shown in Fig. 1. The tool can be flexibly used for the realization of micro-optical free-form elements with profile depths up to ~100µm. More details on the system can be found in [1].

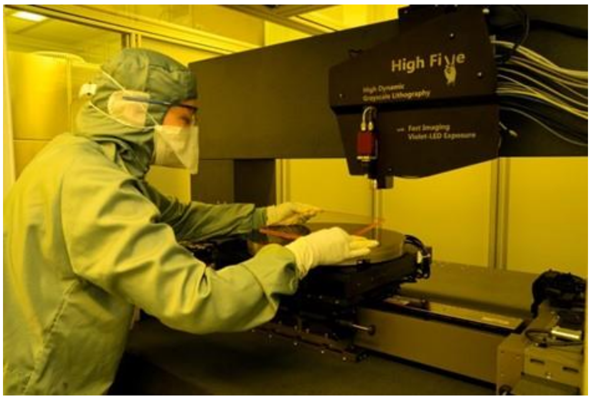

Fig.1. Gray-scale lithography tool developed for the fabrication of micro-optical elements with continuous surface profiles up to 100µm depth.

4. Example: achromatic deterministic diffusers

An important application of micro-optical free-form elements can be found in the field of tailored diffusors. Such elements can be used to generate light distributions with pre-defined envelope to efficiently and homogenously illuminate a target, bend the light on projection screens towards the audience with locally varying deflection angles, homogenize the visual appearance of light sources composed of a larger number of single emitters, and much more.

The flexibility of the design and fabrication approach shall be demonstrated by the example of the diffusion of a broad-band LED light source into an angular distribution having the envelope of the Greek letter "Ω". The designed surface profile of the free-form element is shown in Fig. 2. Its profile depth is 8µm.

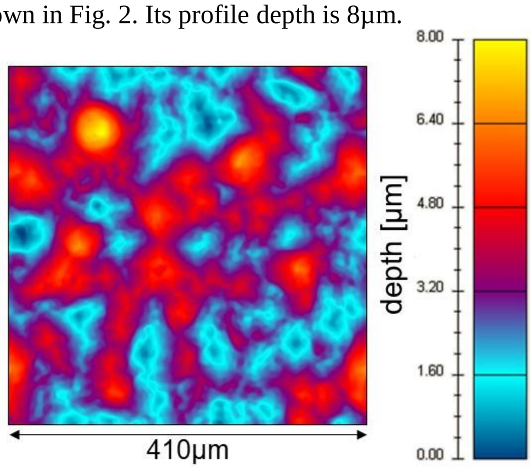

Fig.2. Height profile of a unit cell of the micro-optical free-form element generating an "Ω"-shaped far-field intensity distribution.

Figure 3 shows the resulting far-field intensity distribution for illumination with white light (wavelengths between 480nm and 630nm). The achromatic behavior can clearly be recognized. In particular the appearance of a disturbing 0^{th} diffraction order, which is a typical drawback of conventional DOEs, is completely avoided.

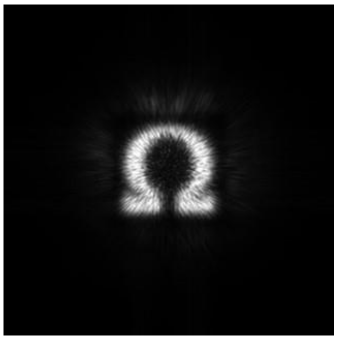

Fig.3. Far-field intensity distribution generated by the element shown in Fig. 2 under white light illumination.

5. Conclusions

The availability of design and fabrication techniques for micro-optical surface profiles having an almost arbitrary surface shape holds huge potential for the optimization of numerous applications. Advances in iterative design algorithms allow the calculation of deep and smooth surface profiles. With such elements the efficient and achromatic generation of arbitrary intensity distributions with a single optical surface becomes possible. Their realization can be done accuratly by modern gray-scale photo-lithographic processes. The latter need a precise control of exposure dose distributions and resist non-linearities.

This way, the micro-optical free-forms are a powerful extension of state-of-the-art optical system design approaches incorporating conventional free-form elements.

6. References

[1] H.-C. Eckstein, U.D. Zeitner, R. Leitel, M. Stumpf, P. Schleicher, A. Bräuer, and A. Tünnermann, „High dynamic grayscale lithography with an LED-based micro-image stepper," Proc. SPIE Vol. 9780, 97800T, (2016).