Enhanced Optical Functionalities by Integrated Ultra-precision Machining Techniques

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Abstract

The integrated fabrication of hybrid optics applying a combination of different ultraprecision machining techniques is the main topic of this contribution. It describes the design considerations, the fabrication process and finally the characterisation of the components based on profilometric analysis of the shape accuracy and the surface roughness as well as experiments proving the optical performance.

1 Introduction

The fabrication of surface structures based on a trans-scale approach leads to a significant enhancement of the performance of optical systems. Herein, the trans-scale approach comprises the realisation of reflective or refractive base profiles with diameters in the order of tens of millimetres and the additional integration of diffractive structures with features sizes of a few micrometres and depths in the submicron range. This type of combined refractive/diffractive or reflective/diffractive components is commonly known as hybrid optics. These elements are the crucial part of numerous highly integrated optical microsystems e.g. for spectroscopic applications [1]. The fabrication of the freeform base profiles by different ultraprecision machining techniques has been demonstrated previously [2].

2 Design and Fabrication

In order to demonstrate the successful fabrication process development, an optical component (shown in Fig. 1) has been designed that monolithically integrates three different optical functionalities: beam deflection (reflective surface), aberration corrected off-axis focusing (freeform surface profile) and spectral decomposition or beam splitting (diffractive grating). The resulting design considerations were taken into account as follows. To guarantee a high surface quality and an excellent machinability copper has been chosen for the substrate material. Diffraction limited off-axis focussing tasks demand for the application of freeform surface shapes. The design of the basic profile for the optical element was carried out using a ray-tracing software (Zemax®). Herein a solid body model of an optimised off-axis parabolic mirror was derived, that was subsequently imported to CAD/CAM software (PowerMill®) to generate the CNC-program needed for the micromilling process. Micromilling was used due to its high flexibility concerning the wide range of machinable geometries. In the final step, a sinusoidal grating being the diffractive optical element was machined into the substrate using ps-laser ablation. The grating was designed for a minimised zero order intensity at a wavelength of 543 nm based on the characteristic groove shape resulting from the laser ablation process [3].

All fabrication steps were performed on a sophisticated 5-axis ultraprecision micromachining centre (Microgantry® nano5X, Kugler GmbH, Salem, Germany) run at the Centre for Micro- and Nanotechnologies (ZMN) of Ilmenau University of Technology. The machine provides a picosecond pulsed laser source for laser ablation and two different air-bearing spindles for mechanical micromachining, i.e. a spindle for fly-cutting as well as a high frequency spindle for micromilling.

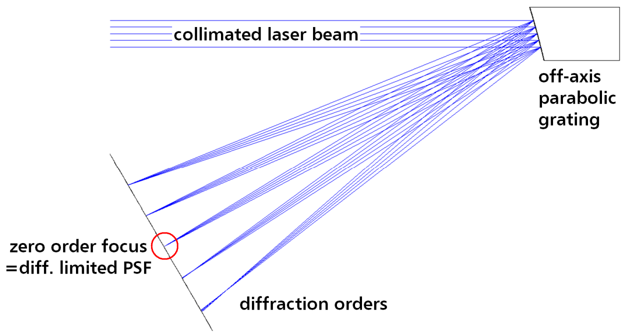

Figure 1: Principle of the hybrid freeform element (off-axis parabolic grating).

3 Characterisation of the Hybrid Optical Freeform Element

The characterisation of the micromilled basic profile as well as the grating fabricated by laser ablation is discussed in the following subsections. Section 3.1 is dedicated to the geometrical features such as shape accuracy and surface quality. Section 3.2 describes the results of the experiments verifying the optical performance.

3.1 Shape Accuracy and Surface Quality

Right after the micromilling process a short shape preserving polishing step was applied to reduce high frequency artefacts resulting from imperfections of the cutting edge and vibrations of the tool. The roughness was reduced from $R_a = 61.5$ nm to $R_a < 3$ nm (Fig 2.). Within a diameter of 5 mm the shape accuracy was determined to be $\Delta z_{RMS} < 75$ nm and $\Delta z_{PV} < 550$ nm. After the laser ablation process the depth of the diffraction grating was measured across the whole element. With an average depth of 207 nm ($\Delta z < \pm 8$ nm) it almost exactly matches the design depth of 208 nm.

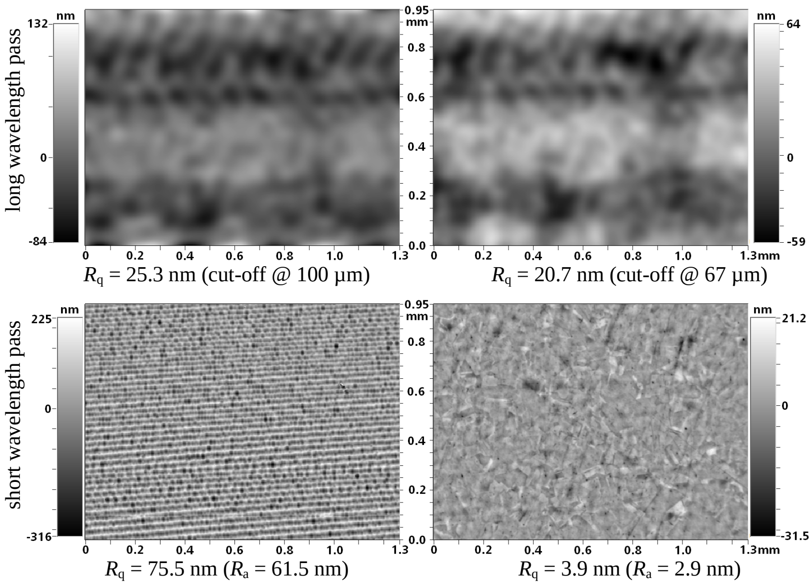

Figure 2: Surface quality before (left) and after polishing (right).

3.2 Optical performance testing

Right after the polishing process the focussing performance of the reflective free-form surface was experimentally verified. The point spread function was found to be nearly diffraction limited. Experiments following the laser ablation process provided the results for the completed system. As shown in Fig. 3, the measured intensity distribution within the diffraction orders of the sinusoidal grating is in excellent agreement with rigorous simulations. Especially the measured zero order efficiency of 0.11 % of the total reflected power is very close to the calculated minimum of

0.08 % [3]. In summary, the experiments confirmed the high expectations regarding the optical performance of the hybrid optical freeform element that arose from the high precision of the integrated fabrication process discussed in section 3.1.

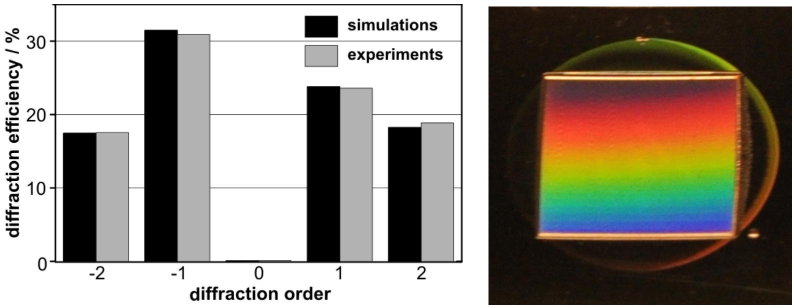

Figure 3: Diffraction efficiencies (left) of the parabolic grating (right).

4 Conclusion and Outlook

The successful integrated fabrication of a hybrid optical element combining the functionalities of beam deflection, diffraction limited focussing and beam splitting was demonstrated at a high level of precision. The very general CAD/CAM based solution of the fabrication task can easily be adapted to future applications like beam shaping, spectral imaging as well as for optimised optical imaging systems.

Acknowledgements

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