Ultraprecision micromilling for the fabrication of monolithically integrated refractive microoptical systems

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Different classes of optical elements combined in a monolithically integrated microoptical system are fabricated using micromilling. On the resulting surfaces the average roughness height was found to be R_a < 40 nm with an overall shape accuracy < 1.6 µm (based on the determination of the radii of curvature).

1 Introduction

Planar microoptical systems integration is a powerful approach for the fabrication of compact optical systems which has been demonstrated for a large variety of applications [1][2][3]. The folded optical axis in combination with planar fabrication technologies enables highly integrated and rugged optical systems. In this geometry specific care is necessary to avoid aberrations resulting from the oblique optical axis. Using diffractive optical elements for this purpose the overall systems efficiency drops down drastically and strongly depends on the spectral bandwidth of the incident light [4]. The refractive implementation on the other hand has been suffering from the lack of fabrication technologies for freeform microoptical elements, so far. To overcome these limitations the fabrication by ultraprecision micromilling is investigated.

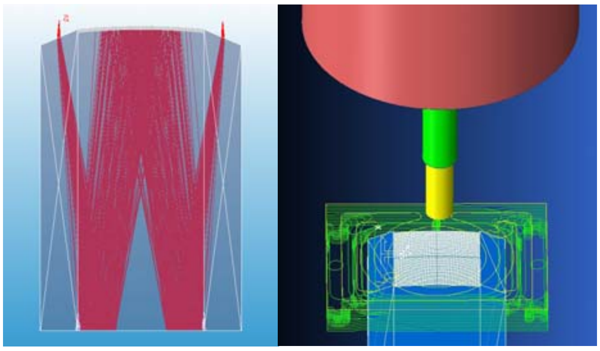


Fig. 1 *Ray-tracing simulations for the optical design using ZEMAX™ (left) and tool trajectories for the rough cutting process generated using PowerMILL™ (right).*

2 Design

The planar integrated microoptical system consists of two refractive coupling prisms (prism angle = 23°) and a reflection-coated element for the imaging functionality. The reflective surface possesses two different radii of curvature in the XZ- and YZ-plane (r_{XZ} = 31.4 mm, r_{YZ} = 30.7 mm). Thus from the technological point of view, it can be seen as a non-rotationally symmetric freeform surface. After the design process using ZEMAX™, a solid model was derived from the systems layout. It was subsequently imported into a CAD/CAM software (PowerMILL™) to generate the tool trajectories for the manufacturing. Fig. 1 shows both steps.

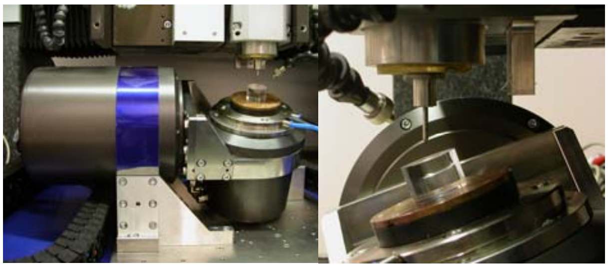


Fig. 2 *Close-up view shows a PMMA substrate mounted on the thermo chuck, a diamond-microcutter as well as the lubrication system.*

3 Fabrication

The fabrication process was carried out in a PMMA substrate on a Microgantry® nano5X ultraprecision machining center (by Kugler GmbH, Salem, Germany, Fig. 2) in two stages – a rough cutting step using a tungsten carbide tool and a finishing step using a ball end diamond-microcutter. For the programming of the tool trajectories a helical machining strategy was chosen for the freeform element with a constant distance of 5 µm between the tool paths. The coupling prisms were fabricated applying a linear raster machining strategy.

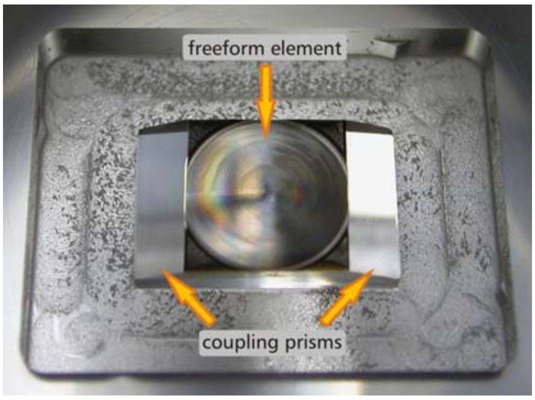
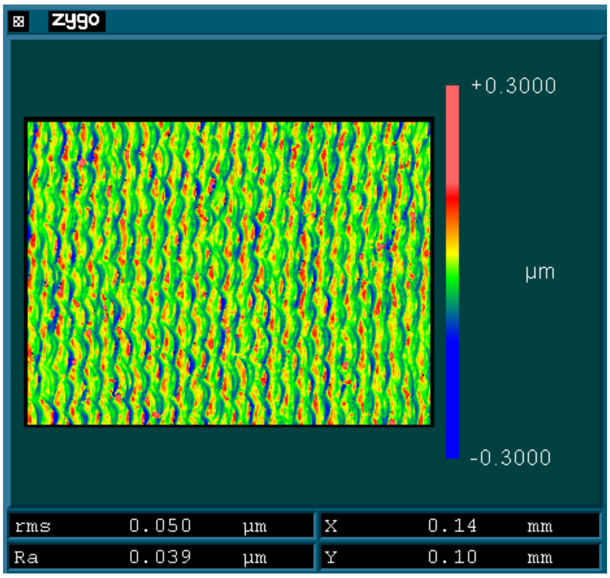


Fig. 3 *Micromilled monolithically integrated system.*

4 Surface roughness and shape accuracy

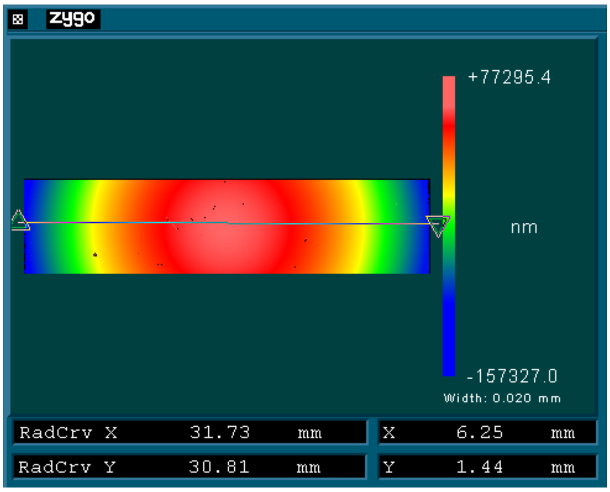
The micromilled optical elements (Fig. 3) were evaluated using scanning white light interferometry directly after the machining process without any subsequent polishing steps. The average roughness height was found to be R_a = 39 nm (Fig. 4).



rms 0.050 µm
Ra 0.039 µm
X 0.14 mm
Y 0.10 mm

Fig. 4 *Evaluation of the surface quality using a NewView™ 7200 by ZygoLOT.*

The deviations between the realized radii of curvature and the results of the design process are in the order of 1 % in the YZ-plane down to 0.3 % in the XZ-plan (Fig. 5). Using these values the absolute difference between the optimum profile and the measured profile can be calculated for the outer parts of the freeform element at a diameter of 6.25 mm to be 1.59 µm and 0.53 µm, respectively.



RadCrv X 31.73 mm
RadCrv Y 30.81 mm
X 6.25 mm
Y 1.44 mm

Fig. 5 *Estimation of the radii of curvature.*

Two main factors can be identified that strongly influence the achievable surface quality. On the microscopic level it is the chosen machining strategy, as the constant tool path distances together with the tool rotation result in a periodicity of the tool traces showing different but characteristic spatial frequencies. On the macroscopic level it is the geometry of the cutting edge. Even small deviations from the optimum shape reduce the shape accuracy of the micromilled elements, accordingly.

5 Optical experiments

The experiments for the verification of the optical performance of the monolithically integrated systems were conducted based on the determination of the point spread function (Fig. 6). They were carried out using the beam of a He-Ne laser at a wavelength of 632.8 nm coupled into a single mode fiber. The fiber tip (5 µm core diameter) served as a point source and could be aligned in the object plane. After propagating through the planar integrated optical system the output plane is imaged by a microscope objective onto a CCD-chip. The 1/e²-diameter of the spot in the image plane was found to be 9 µm. Thus a very good optical performance could be demonstrated.

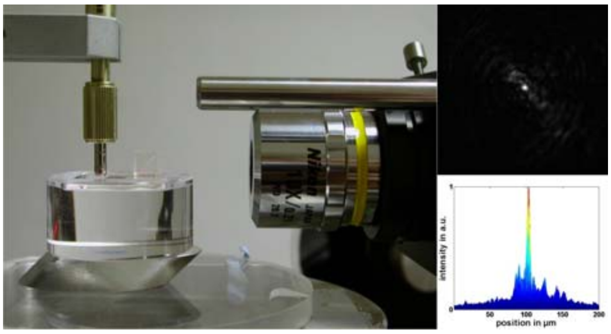


Fig. 6 *Experimental setup and point spread function in the image plane for the monolithically integrated system.*

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