Simulation and measurement of thermo-optical effects in an f-theta lens at high laser power

Tobias Bonhoff*, Christoph Gayer**, Jochen Stollenwerk*,**, Peter Loosen*,**

*RWTH Aachen University, Chair for Technology of Optical Systems, Aachen, Germany
**Fraunhofer Institute for Laser Technology, Aachen, Germany

mailto:tobias.bonhoff@tos.rwth-aachen.de

The use of high power lasers in material processing is accompanied by thermal effects that can degrade the stability and process quality. This paper discusses the simulation and measurement of a thermally induced focus shift by means of a ZnSe f-theta lens.

1 Introduction

The available laser powers steadily increase and lead to increasing thermal loads on the optical elements for beam guiding and shaping. Absorption of laser energy in the bulk material and the coating causes local heating, which results in an inhomogeneous refractive index profile and surface deformations. This leads to a focus shift and higher order aberrations, which for instance decrease the quality of a coaxial process monitoring [1]. As basis for a compensation, we model these thermo-optical effects [2].

2 Modeling of Thermo-Optical Effects

Commonly, optic designers use ray-tracing software for analyzing and optimizing optical systems. But these programs only enable a very basic thermal analysis such as a homogeneous temperature increase. Complex thermal loads and cooling conditions cannot be taken into account. A Finite Element Analysis (FEA) is needed for computing temperature profiles and surface deformations for complex boundary conditions. However, a profound optical analysis is not possible within a FEA. Thus, we couple FEA and ray-tracing [3][4].

The FEA yields discrete temperature and deformation data for each node of the mesh, but the ray-tracing requires continuously differentiable functions for the refractive-index profile [3] and the surface deformation [4]. At our Chair, a weighted least squares approximation algorithm has been developed in order to transfer the discrete data of the FEA to the optical analysis in Zemax OpticStudio™.

3 Setup and Focus Shift Measurement

In the experiments, a CO_2 laser (FEHA 600) with up to 600 W power is used. The raw beam diameter is 13 mm and the beam quality $M^2 < 1.2$. Behind a laser scanner, a ZnSe f-theta lens is placed (Fig. 1). It features a focal length of 300 mm and scan angles up to 20° are feasible. The beam caustic, the waist radius, and the waist location z_0 are measured using the PRIMES FocusMonitor. The focus shift is determined by measuring the waist location z_0 for different laser powers. The system is only analyzed at 0° scan angle. For each power level, three caustic scans are performed and the mean value of the focus shift is computed. The PRIMES software uses the method of second moment (ISO 11146) for computing the radii and the beam caustic.

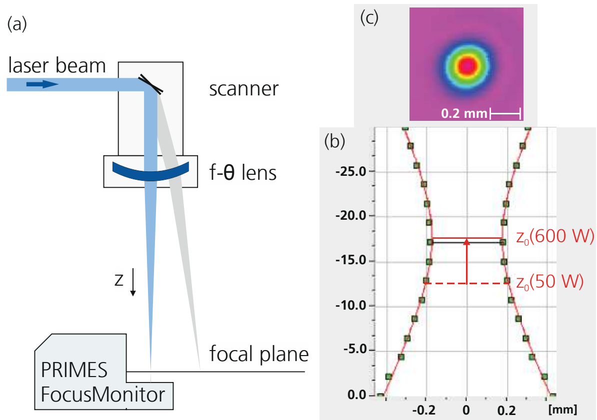

Fig. 1 *Experimental setup (a): The focus shift of the ZnSe f-theta lens is measured at 0° scan angle using the PRIMES FocusMonitor. Beam caustic (b) and intensity profile close to the focal plane (c) at 600 W.*

4 Simulation

The thermal and structural analyses are performed using ANSYS® Mechanical and APDL scripting for defining the Gaussian shaped thermal loads. As bulk and surface absorption, we use the values of a calorimetric measurement of a comparable ZnSe lens from II-VI Inc., which absorbs approximately 0.1% in the coating and 0.06%/cm in the bulk. The f-theta lens is not actively cooled. Heat can only dissipate via convection (heat transfer coefficient of 2 W/(m² K)) and via radiation to the ambient air. The thermal analysis yields a peak temperature of about 70°C at 600 W laser power. For the structural analysis, the clamping of the lens is idealized by appropriate boundary conditions. The maximum deformation is 8 µm.

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The FE data are approximated using our interface program and transferred via user defined surface DLLs to OpticStudio™. The location of the focal plane is obtained via an optimization of the RMS spot size. The resulting focus shift is depicted in Fig. 2. Thereby, the change in refractive index (dn/dT) contributes about 93% to the focus shift and the surface deformation about 7%. The ratio of both effects depends on the material properties and the lens geometry. Since the absorption of the f-theta lens has not been measured, the simulation is repeated for 0.2% absorption per coating. Typical absorption values in AR-coatings on ZnSe are in the range of 0.1–0.2% [5]. The resulting slopes of the focus shift are listed in Tab. 1.

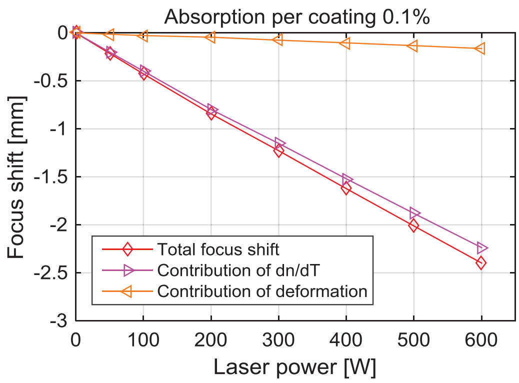

***Fig. 2** Simulated focus shift in dependence of the laser power. The deformation contributes about 7%.*

Absorption per coating [%]	Absorption coefficient bulk [%/cm]	Focus shift [mm/100 W]
0.1	0.06	−0.40
0.2	0.06	−0.74

***Tab. 1** Focus shift in dependence of the absorption.*

Although it is not part of the experiments, the focus shift is computed for different scan angles up to 20°. As expected, the FEA yields a non-rotational symmetric temperature distribution. Compared to 0°, the temperature in the static state is higher. This causes a nonlinear increase of the shift with increasing scan angles. The cold optic features a slight field curvature of −0.11 mm at 20°, visualized by the blue line in Fig. 3. This field curvature increases when the optic heats up. At 20° scan angle, the additional field curvature due to thermal effects is −0.29 mm.

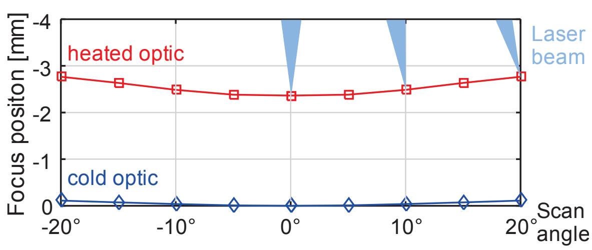

***Fig. 3** For non-zero scan angles, the focus shift in the steady state leads to an increase of the field curvature.*

5 Results

The measured focus shift scales linearly with the laser power (Fig. 4). At 600 W, the focal plane is shifted 5.4 mm towards the backside of the lens. A linear fit yields a slope of −0.89 mm/100 W.

When comparing the experimental and simulative results in Fig. 4, it can be seen that the linear increase of the focus shift with the laser power is predicted by the simulation. The measured slope is about 20% larger than the simulation at 0.2% absorption per coating. Since there are a couple of uncertainties, such as an unknown state of contamination of the lens and inaccuracies because of idealized thermal and mechanical boundary conditions, the experiment and simulation are in good agreement.

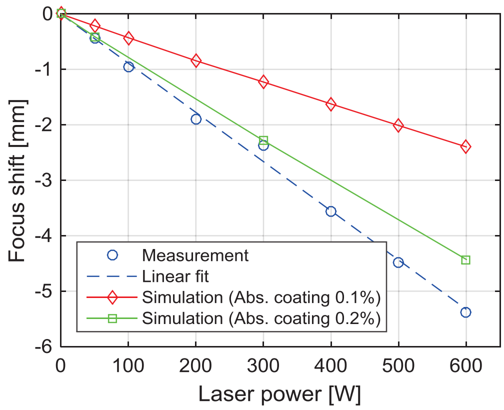

***Fig. 4** Comparison of the focus shift measurement and the simulation for two different absorptions per coating.*

For the future, the measurement of the scan angle dependent focus shift is planned.

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