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Measurement and control system for compensation of thermal effects in laser material processing

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Abstract

Thermal lensing leads to quality losses or, in extreme cases, to the abortion of the whole laser machining process. Here, we present a device for the inline measurement and compensation of the thermal focus shift. For the measurement, the diffraction pattern visible in the working plane created by an amplitude mask is used. By a readjustment of the position of the focusing element the thermal focal shift is compensated.

Keywords: laser material processing; thermal effects; focus compensation, optical design

1. Introduction

The use of steadily increasing laser powers in laser material processing leads to increasing thermal effects in optical systems for beam guidance, focusing and shaping. Although the choice of low-absorbing optical materials, such as fused silica, leads to a reduction of the so-called thermal lens effect, this effect cannot be sufficiently prevented in the range of several kilowatts of laser power (Reitemeyer et al., 2009; Scaggs et al., 2010; Carpenter et al., 2012.). A thermally induced focus shift is the consequence, which leads to quality losses or, in extreme cases, to the abortion of the whole laser machining process (Piehler et al., 2012). For the compensation of the focus shift, a precise measurement of the focal position relative to the processing level is essential. Most of the measurement methods reported in the literature are only able to compare the actual beam size with the target beam size at the processing level without thermal effects (Abt et al., 2008; Weick 2015; Guttman et al., 2011; Yamazaki et al., 2005; Stork, 2011; Warm et al, 2012). The directional dependence

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of the focus shift, on the other hand, is not accessible for these measurements. For laser beams a few millimeters in diameter, a measurement of the total amount of defocus and its direction is possible with an out-of-focus wavefront sensor (Bell et al., 2016; Mann et al., 2015). In this paper, we present a measurement and control system using a so called Bahtinov-mask in the beamline. In chapter 1.1 the functional principal of the Bahtinov-mask and the experimental setup is explained. Afterwards, in chapter 1.2. the measurement principle is validated. Finally, the validated setup is used for the measurement of thermal focal shifts (chapter 1.3.). The paper ends with a conclusion and outlook.

2. Functional principal and experimental setup

The working principle of the Bahtinov-mask is displayed in Figure 1.

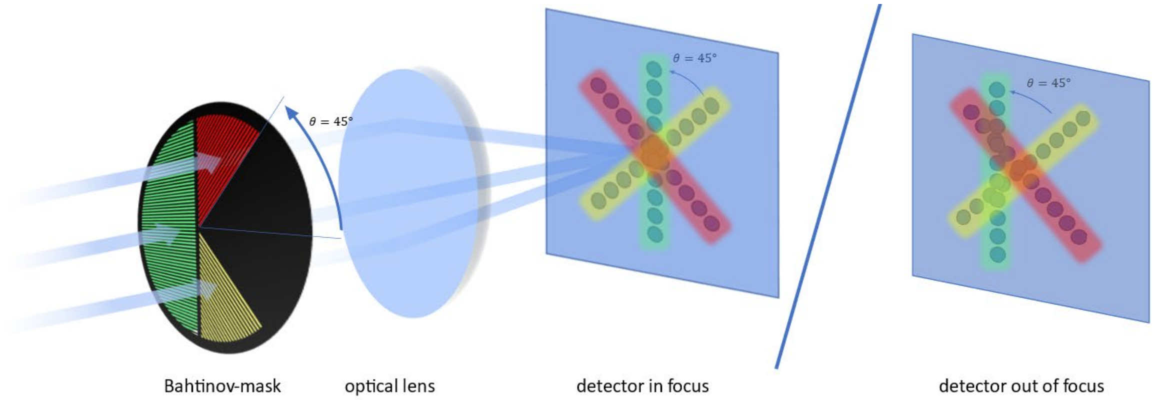

Fig. 1. Illustration of the functional principle of the Bahtinov-mask

The Bahtinov-mask is an amplitude mask which consists of three different diffraction gratings. Behind the grating a focusing lens is placed. For illustration purposes each grating, and the corresponding diffraction orders are marked in the same color. If the mask is coherently illuminated, each grating produces different diffraction orders in the focal plane. The diffraction orders of each grating follow a straight line. The superposition of the diffraction orders of the different gratings results in a characteristic diffraction pattern. When the detector plane is in focus, the green, the red and the yellow lines intersect at a single point. When the detector plane is outside the focus, the observed diffraction pattern is deformed so that the intersection of the red and yellow lines no longer intersects with the green line. The diffraction orders marked in green, and the diffraction orders marked in red and yellow move in opposite directions (see Figure 1). The different movement directions are based on the asymmetry of the diffraction mask. The shortest distance d in between the crossing point of the red and yellow line and the green line is proportional to the amount of defocus Δz. To determine the exact focal shift from the measurements for the specific setup, the proportional constant c must be determined. The optical setup used is shown in Figure 2. Instead of the optical lens in Figure 1, a focusing unit placed on top of a translation stage was used. The focusing unit is a glass lens with a focal length of $f = 150\ \mathrm{mm}$. The light source used is a laser with a wavelength of $\lambda = 1064\ \mathrm{nm}$. The intensity distribution next to the focal plane is measured by a CCD camera.

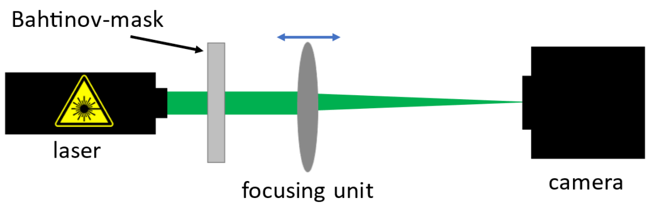

Fig. 2. Experimental setup

3. Validation of the measurement principle

To determine the proportional constant c, first the translation stage is shifted to different positions to achieve a known amount of defocus of Δz. For each position the distance d is extracted from the diffraction pattern. Finally, the calibration factor is determined via a linear fit. The measured values already corrected by the calibration factor are displayed in Figure 3. This way, it was possible to measure the amount of defocus within a range of $16.5\ \mathrm{mm}$. For larger distances, the different diffraction orders become larger and begin to overlap. This leads to a misidentification of the different diffraction orders by the algorithm used to post-process the raw images.

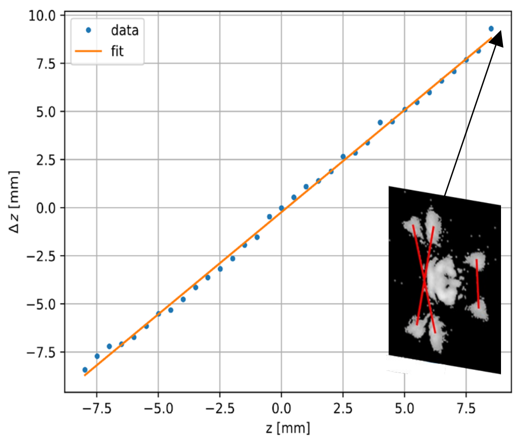

Fig. 3. Measured distances at known defocus

To determine the measurement accuracy of the absolute focus position, focus measurements based on the diffraction pattern of the Bahtinov-mask are compared with the focus position extracted from a caustic measurement. The results are shown in Figure 4.

With the measurements using the Bahtinov-mask, a focal position of $19.008\ \mathrm{mm}$ was obtained. With the caustic measurements, the focal position was determined at a position of $19.043\ \mathrm{mm}$ and thus the difference is $35\ \mu\mathrm{m}$. The beam caustic measurements therefore confirm the validity of the newly introduced measurement principle.

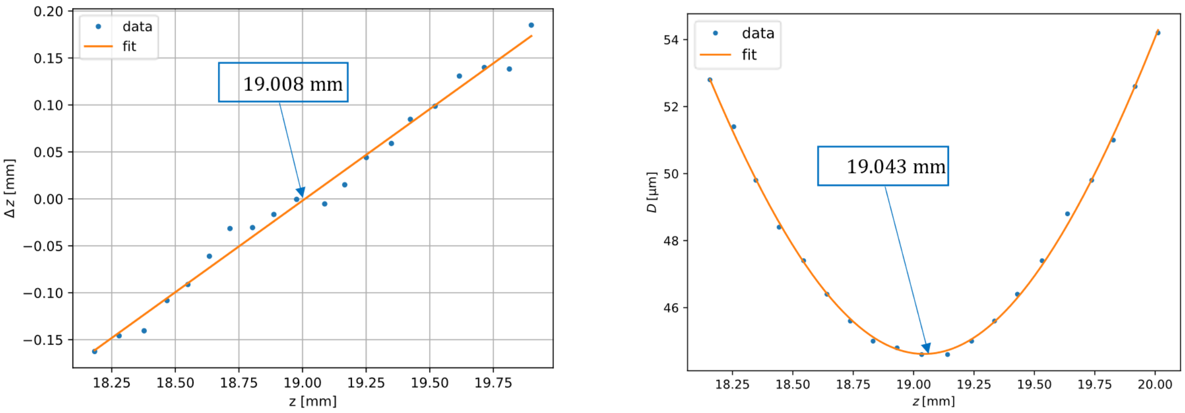

Fig. 4. Comparison of the focus position determined via diffraction pattern of the Bahtinov-mask (left) and via beam caustic measurements (right)

4. Measurement of thermal effects

In the following, the focusing unit is replaced by a combination of a glass and an acrylic lens. The total focal length changes to $f = 138.9$ mm. Due to the comparatively high absorption of the acrylic lens in comparison to glass, thermal effects are expected at already a few watts of laser power. The measured thermal focal shift Δz is displayed in Figure 5. As the exposure time increases, a smaller focus shift per time interval is observed and the focus shift approaches a certain saturation level. The total amount of defocus scales with the laser power being used. On the right side of Figure 5, the measured thermal focus shift at 15 W of laser power without compensation is compared to the case with compensation. Therefore, the defocus calculated via the diffraction pattern of the Bahtinov-mask is used to shift the translation axis accordingly. With compensation, the observed focus shift reduces from maximum 3.5 mm to less than 0.5 mm. Especially for longer processing times, the focal shift fluctuates around 0.0 mm. For shorter processing times, the small deviations from zero

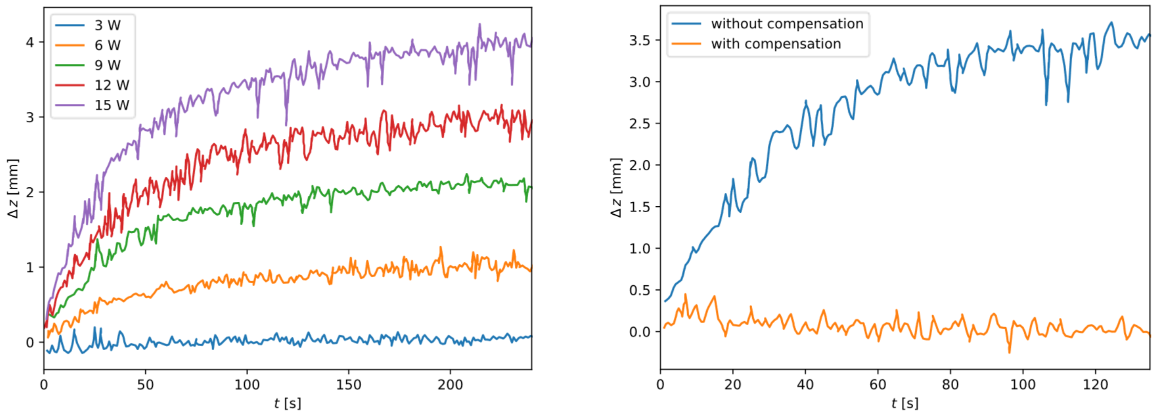

Fig. 5. Measurement of thermal focal shifts. Left: Without compensation. Right: With and without compensation for 15 W.

can be explained by the fact that the focus shift increases during the time of data evaluation, so that the value used for compensation is systematically too low.

5. Conclusion

In this paper, a novel measurement and control system for the compensation of thermal effects in laser material processing was presented. With the measurement and control system presented, focus deviations in the range of $16.5\ \mathrm{mm}$ can be detected. The accuracy of tracking the focus deviation has been compared to a caustic measurement of the beam and agrees to within 35 microns. Furthermore, the measurement and control system has been used to measure thermal effects and compensate them in real time. In the future, the coaxial integration of the system into a laser machining device is targeted.

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